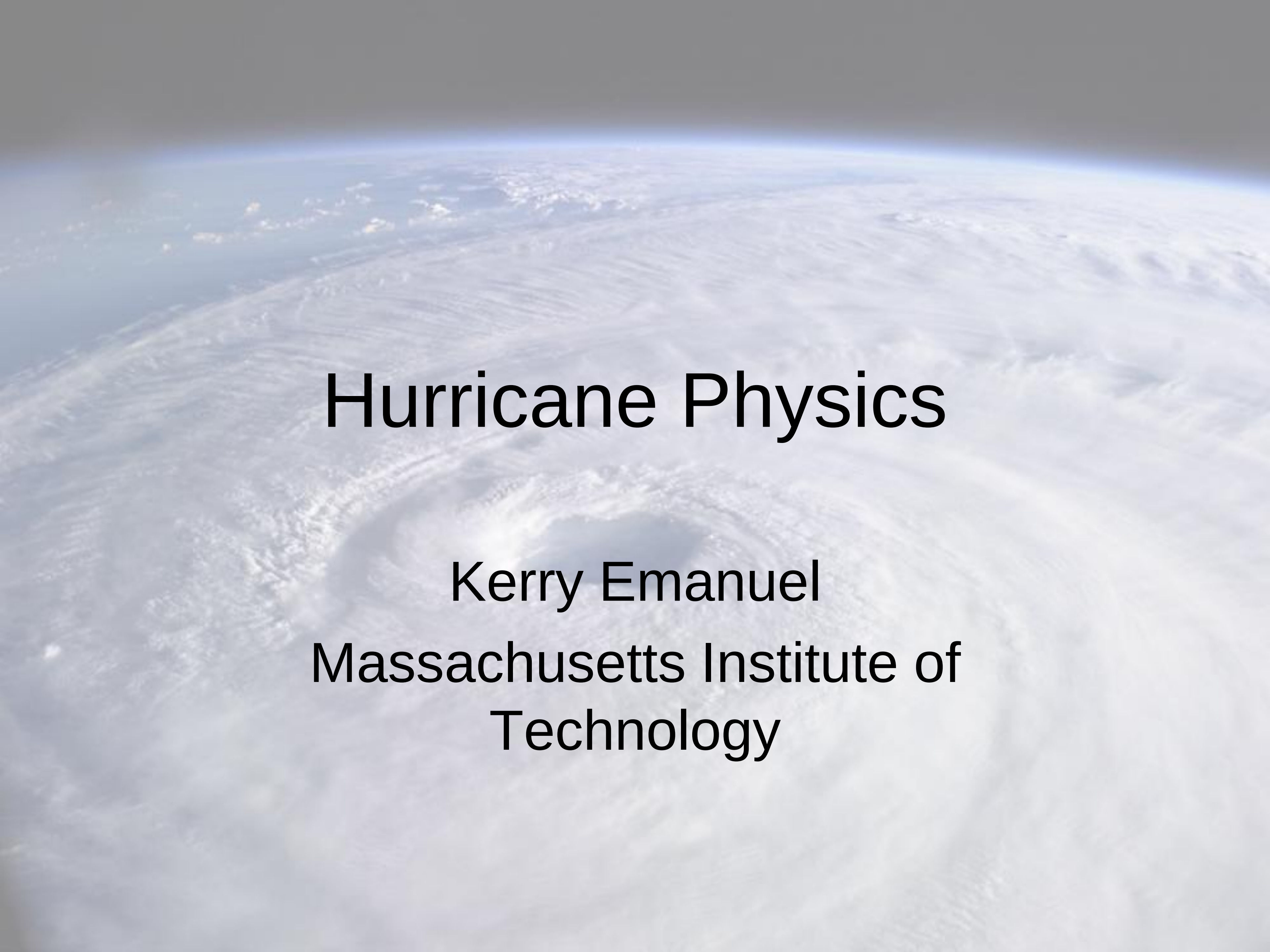
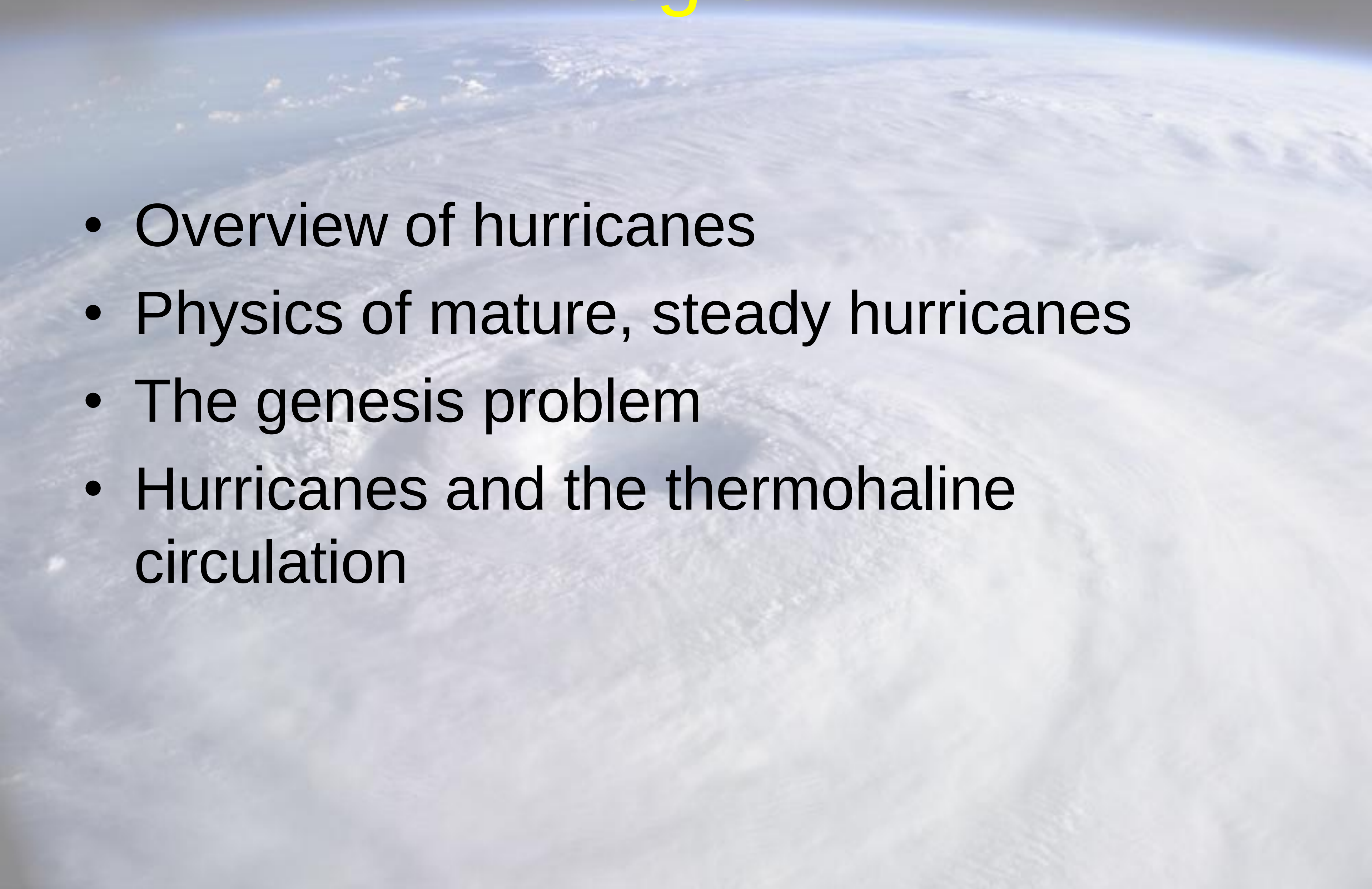


Hurricane Physics

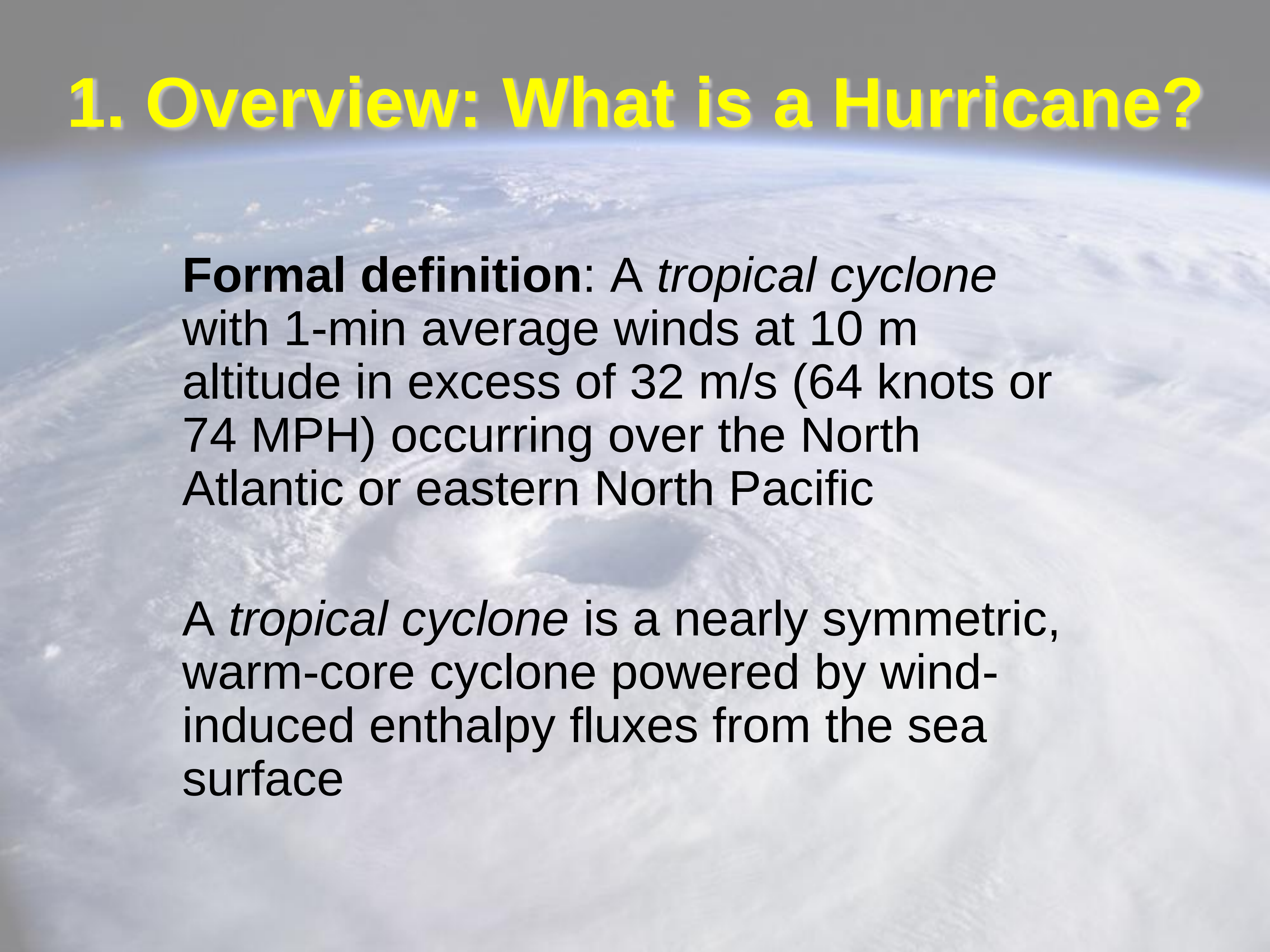
Kerry Emanuel

Massachusetts Institute of Technology

Program



- Overview of hurricanes
- Physics of mature, steady hurricanes
- The genesis problem
- Hurricanes and the thermohaline circulation

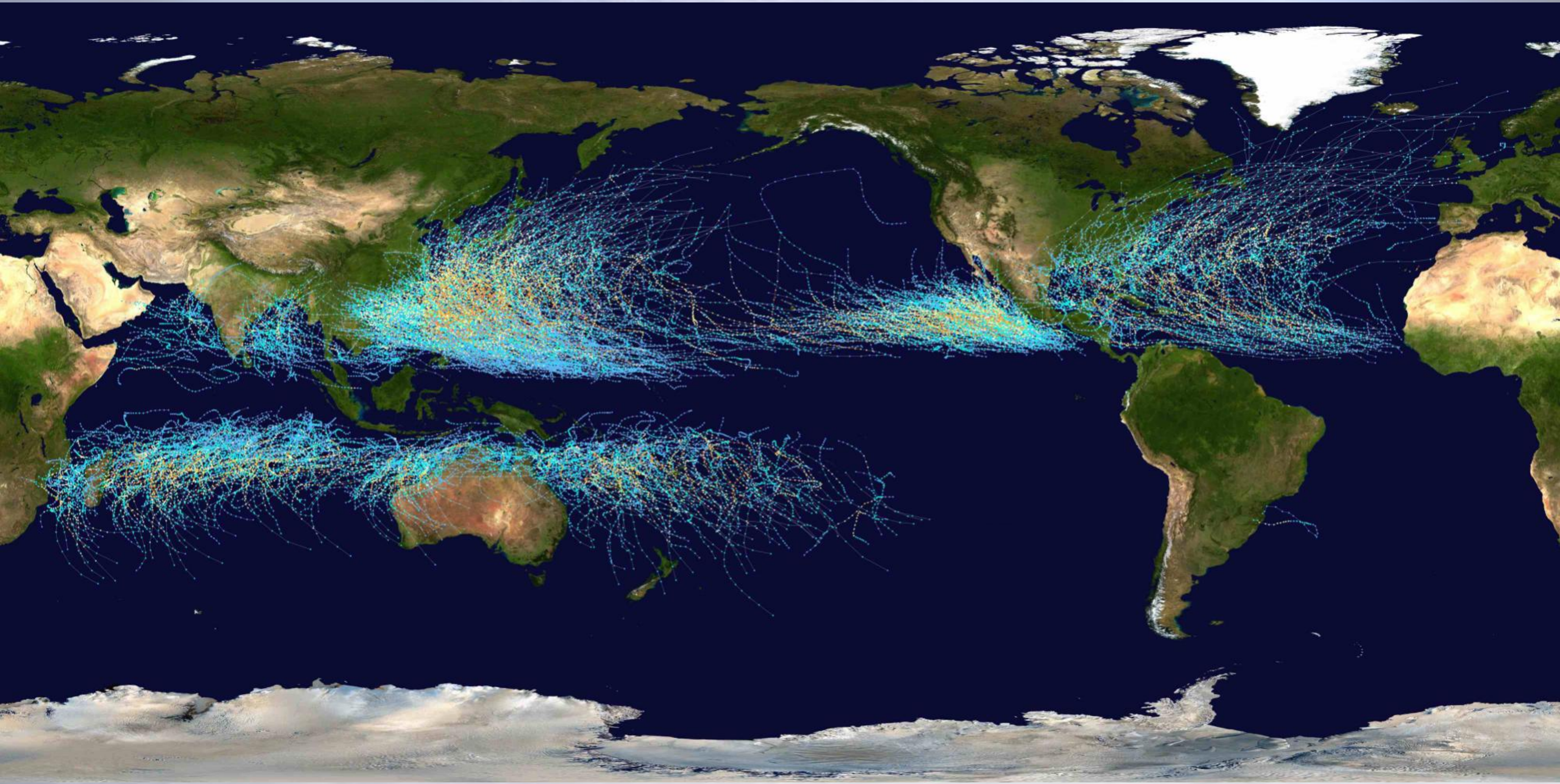


1. Overview: What is a Hurricane?

Formal definition: A *tropical cyclone* with 1-min average winds at 10 m altitude in excess of 32 m/s (64 knots or 74 MPH) occurring over the North Atlantic or eastern North Pacific

A *tropical cyclone* is a nearly symmetric, warm-core cyclone powered by wind-induced enthalpy fluxes from the sea surface

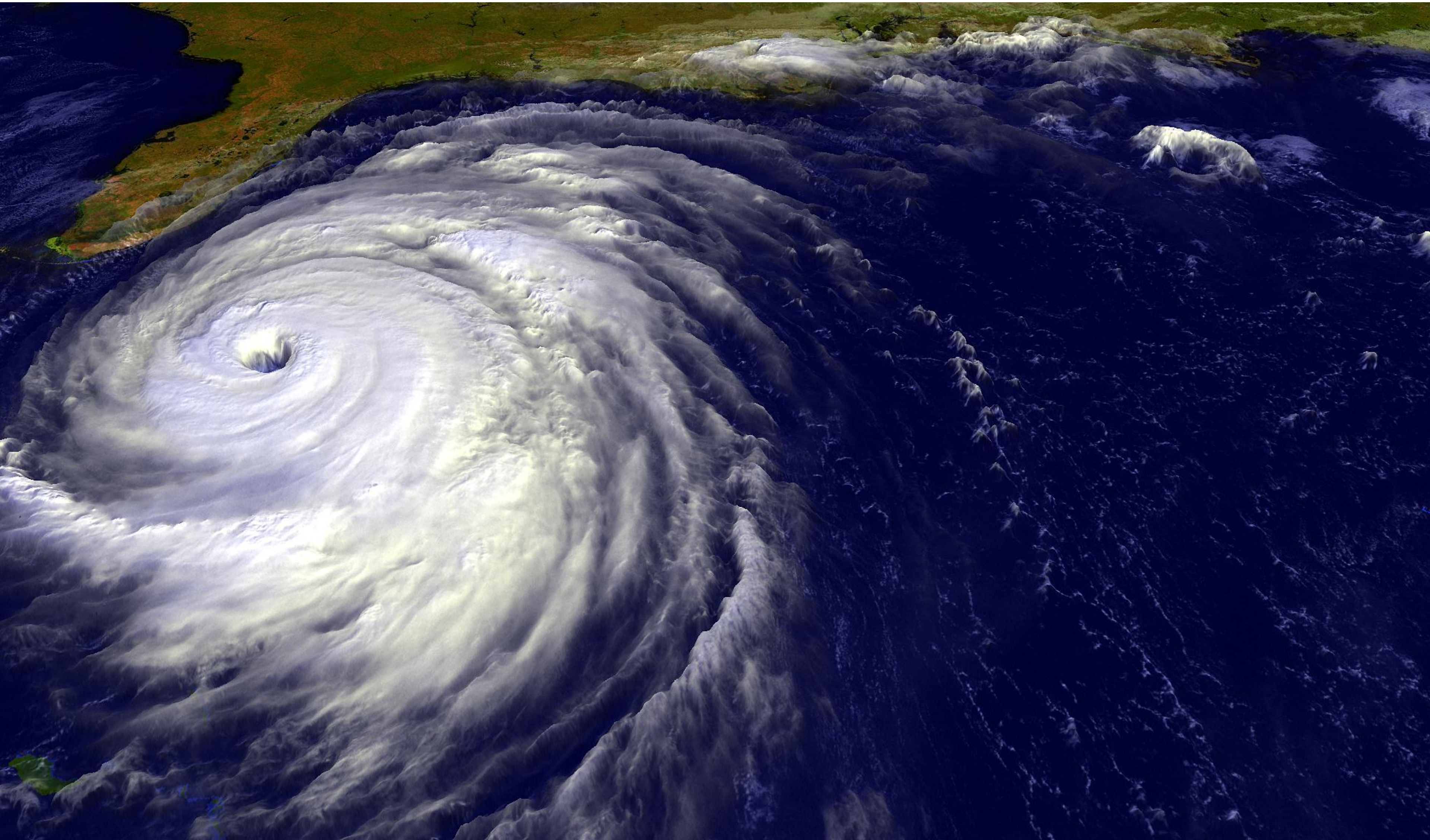
Tracks of all tropical cyclones, 1985-2005



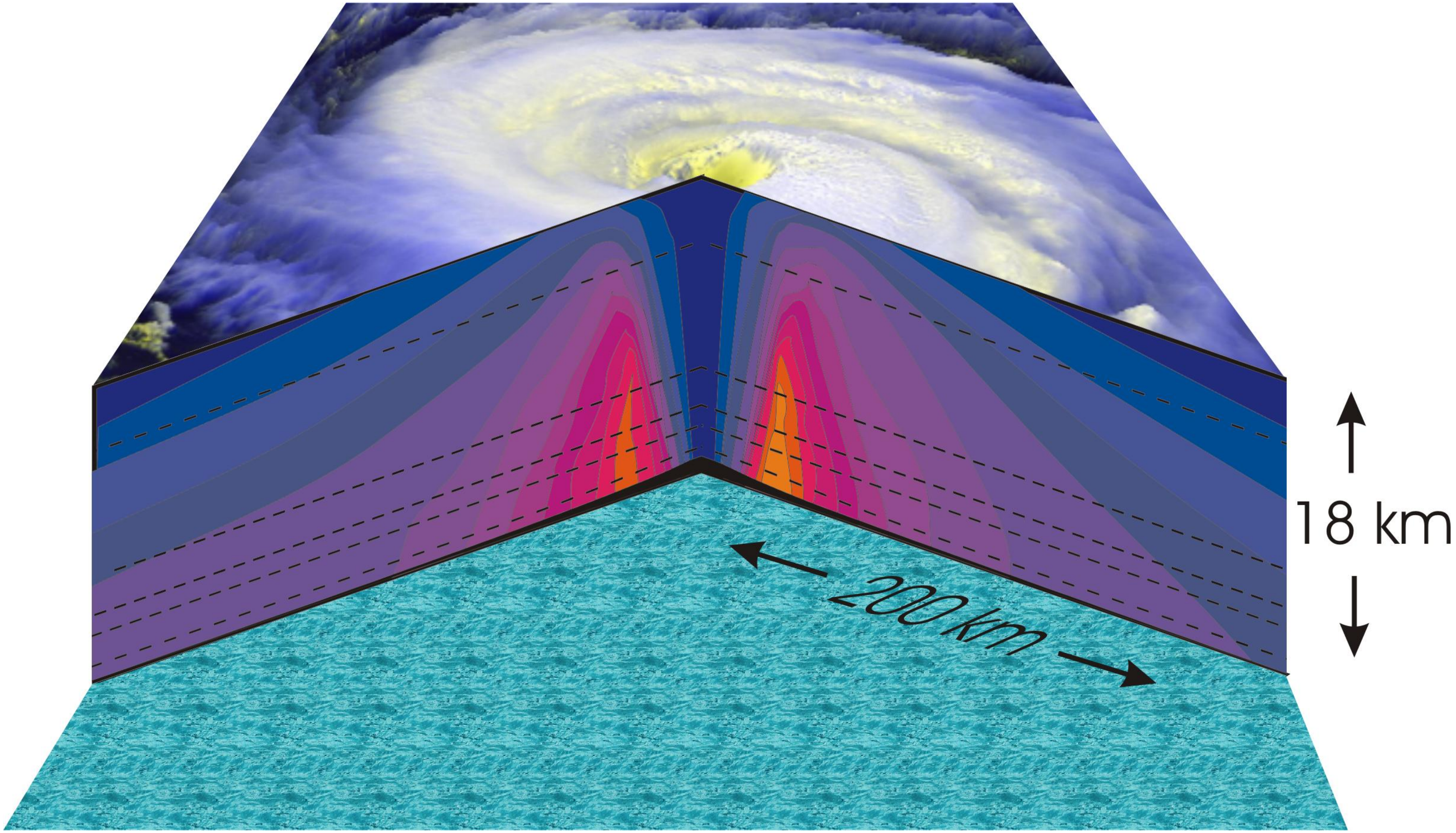
Source: Wikipedia

Hurricane Structure

The View from Space



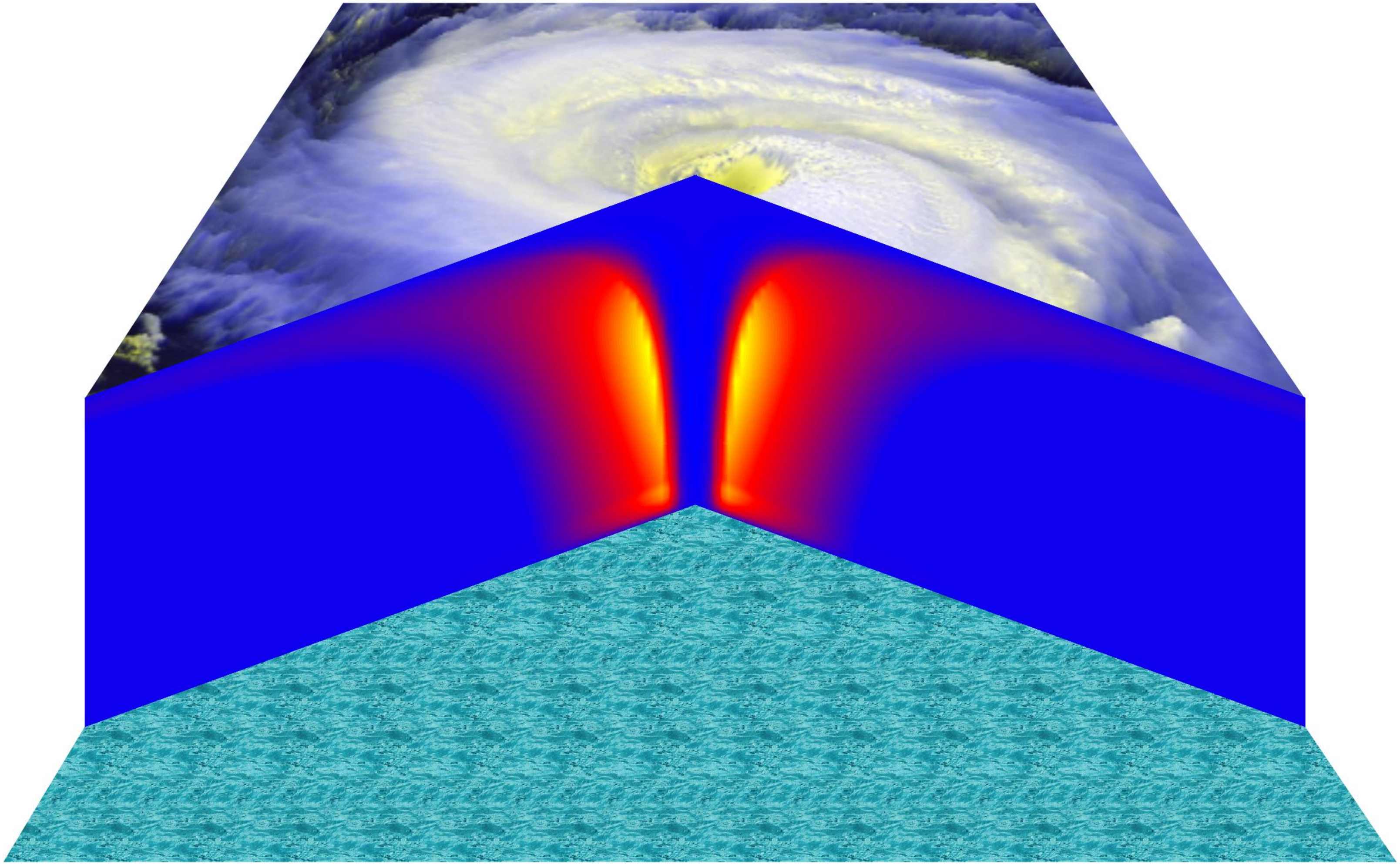
Hurricane Structure: Wind Speed



Azimuthal component of wind

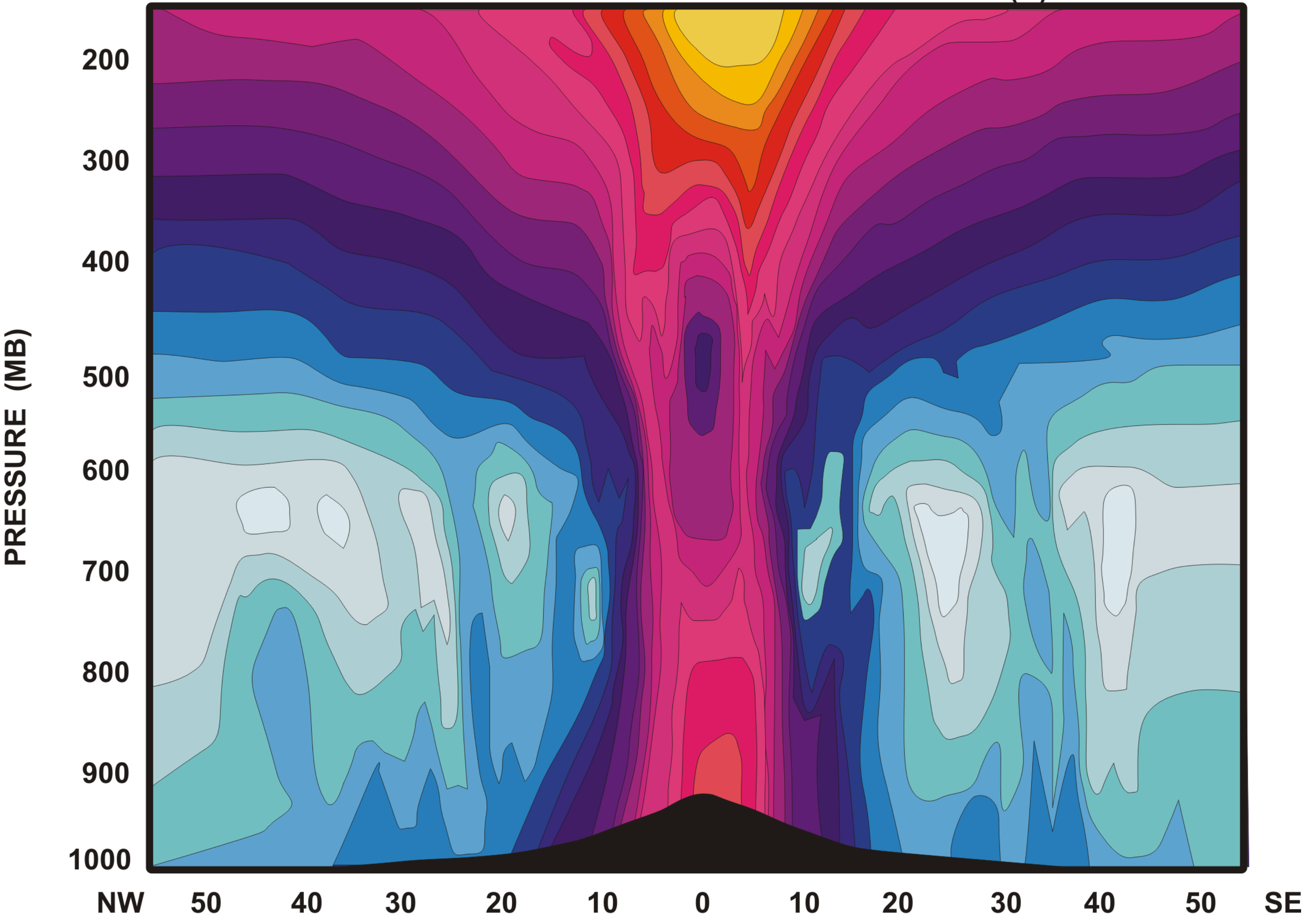
< 11 5 ms^{-1} - > 60 ms^{-1}

Vertical Air Motion



Updraft Speed

Strong upward motion in the eyewall

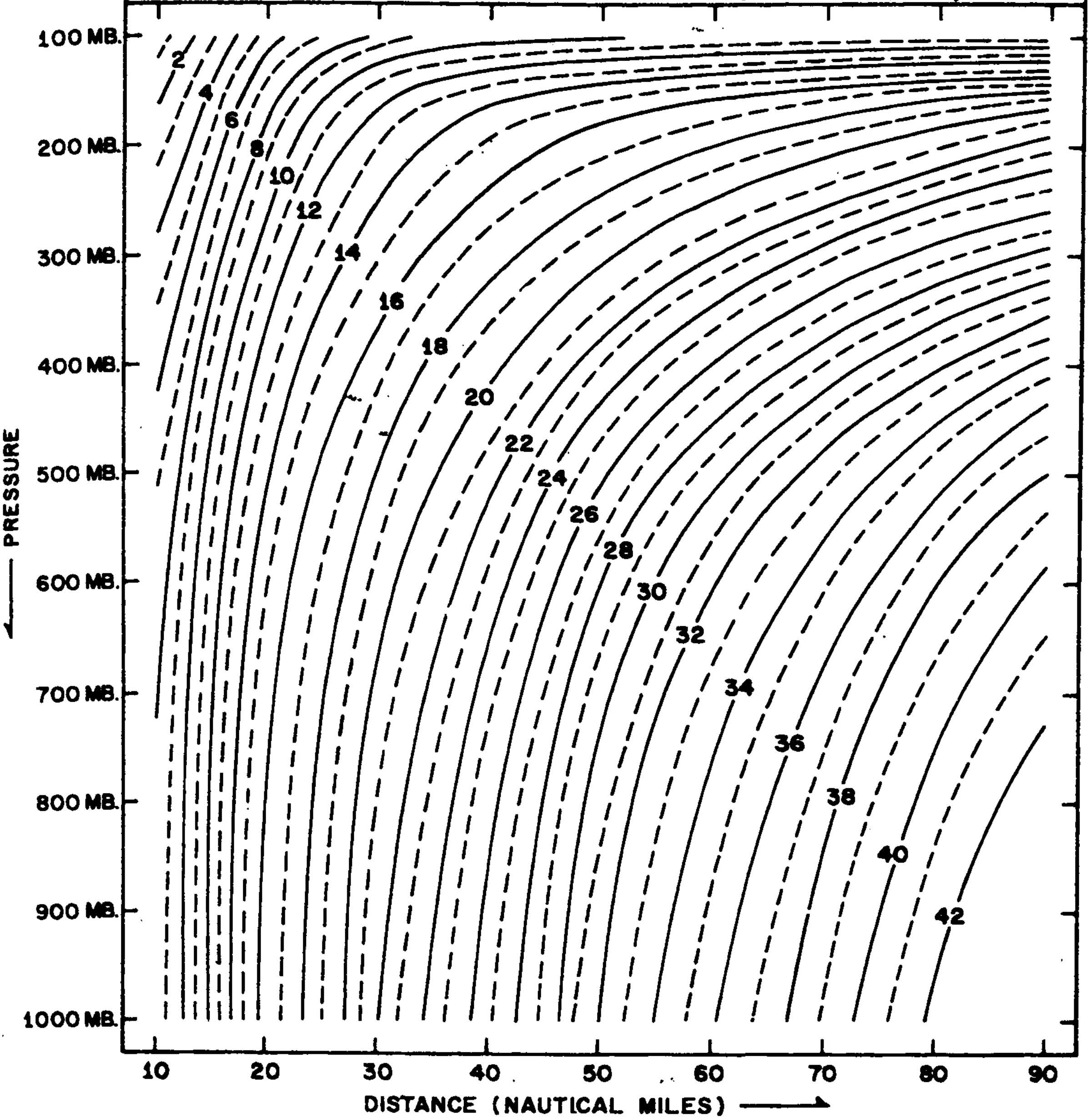


HURRICANE INEZ

SEPTEMBER 28, 1966

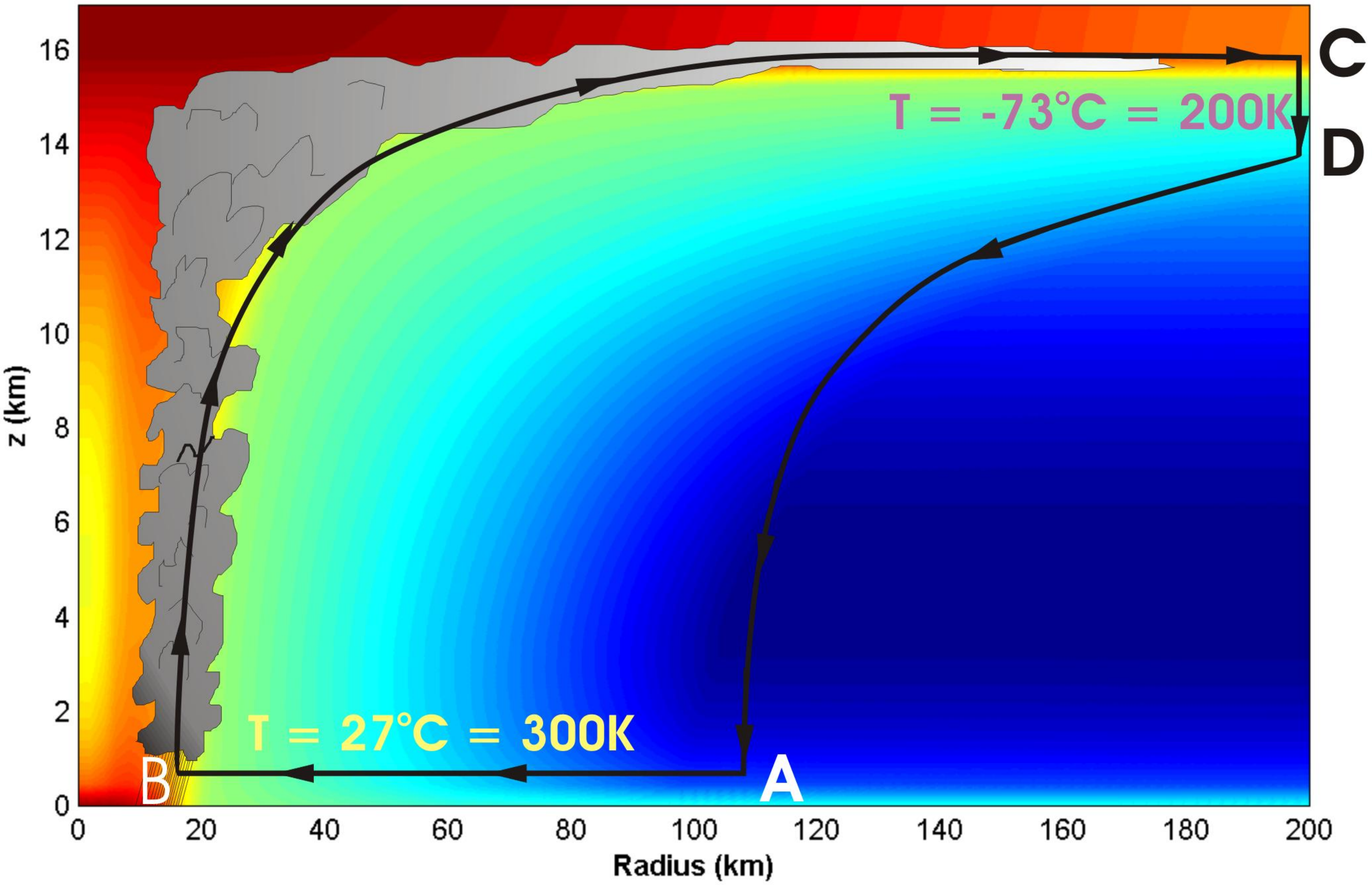
EQUIVALENT POTENTIAL TEMPERATURE (K)

HURRICANE "HILDA" OCTOBER 1, 1964
VERTICAL CROSS-SECTION OF ABSOLUTE ANGULAR MOMENTUM $\overline{V}_\theta r + fr^2/2$ UNITS ($100\ \mathrm{N.Mi.}^2/\mathrm{hr.}$)



Physics of Mature Hurricanes

Energy Production



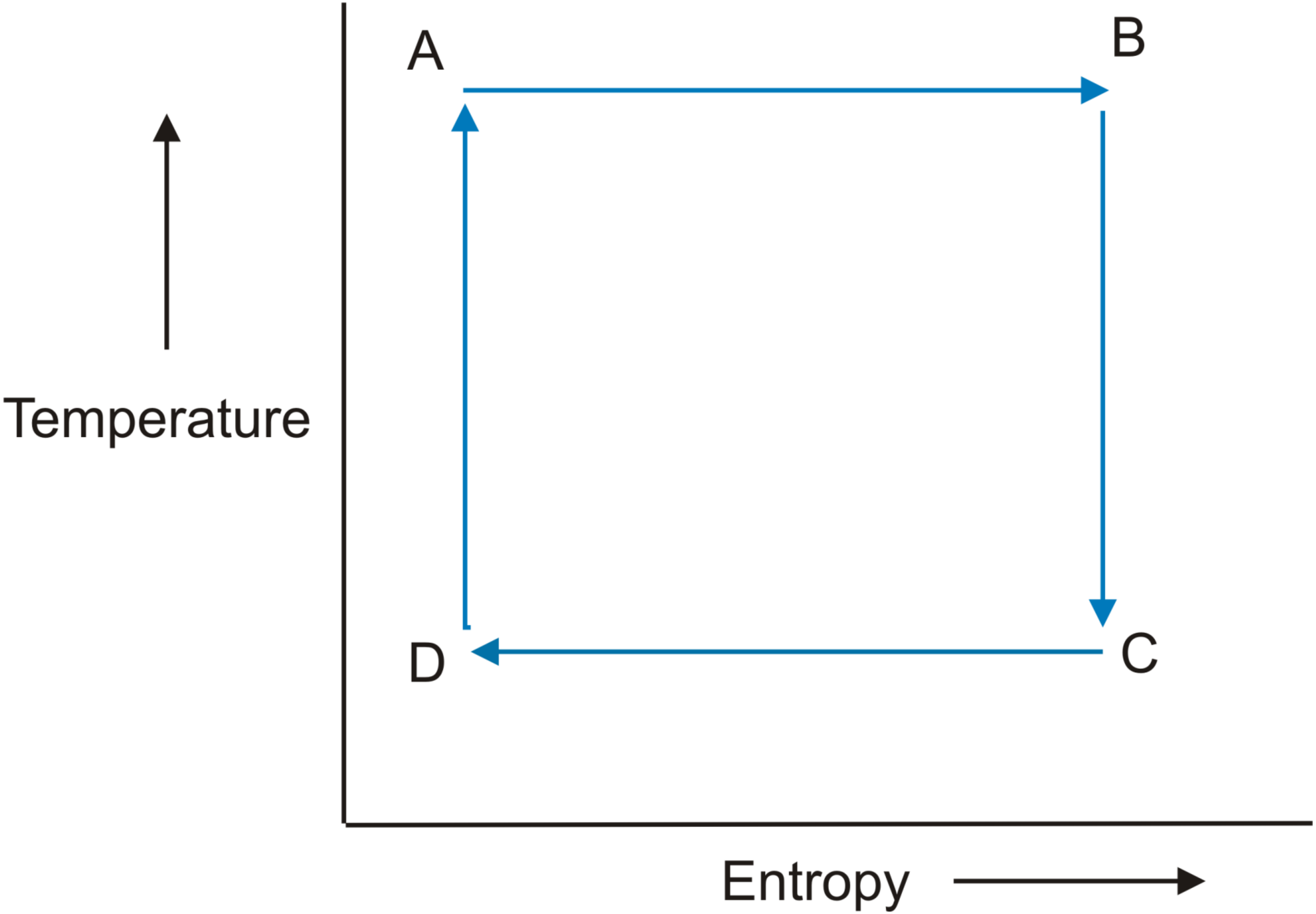
Carnot Theorem: Maximum efficiency results from a particular energy cycle:

- Isothermal expansion
- Adiabatic expansion
- Isothermal compression
- Adiabatic compression

Note: Last leg is not adiabatic in hurricane: Air cools radiatively. But since environmental temperature profile is moist adiabatic, the amount of radiative cooling is the same as if air were saturated and descending moist adiabatically.

Maximum rate of working:

$$W = \frac{T_s - T_o}{T_s} \dot{Q}$$


A
B
C
D
Temperature
Entropy

Total rate of heat input to hurricane:

$$\dot{Q} = 2\pi \int_0^{r_0} \rho \left[C_k |\mathbf{V}| \left(k_0^* - k \right) + C_D |\mathbf{V}|^3 \right] r\,dr$$

Surface enthalpy flux

Dissipative heating

In steady state, Work is used to balance frictional dissipation:

$$W = 2\pi \int_0^{r_0} \rho \left[C_D |\mathbf{V}|^3 \right] r\,dr$$

Plug into Carnot equation:

$$\int_0^{r_0} \rho\left[C_D\,|\mathbf{V}|^3\right] r\,dr = \frac{T_s - T_o}{T_o} \int_0^{r_0} \rho\left[C_k\,|\mathbf{V}|\left(k_0^* - k\right)\right] r\,dr$$

If integrals dominated by values of integrands near radius of maximum winds,

$$\rightarrow \quad |V_{\max}|^2 \cong \frac{C_k}{C_D}\frac{T_s - T_o}{T_o}\left(k_0{}^* - k\right)$$

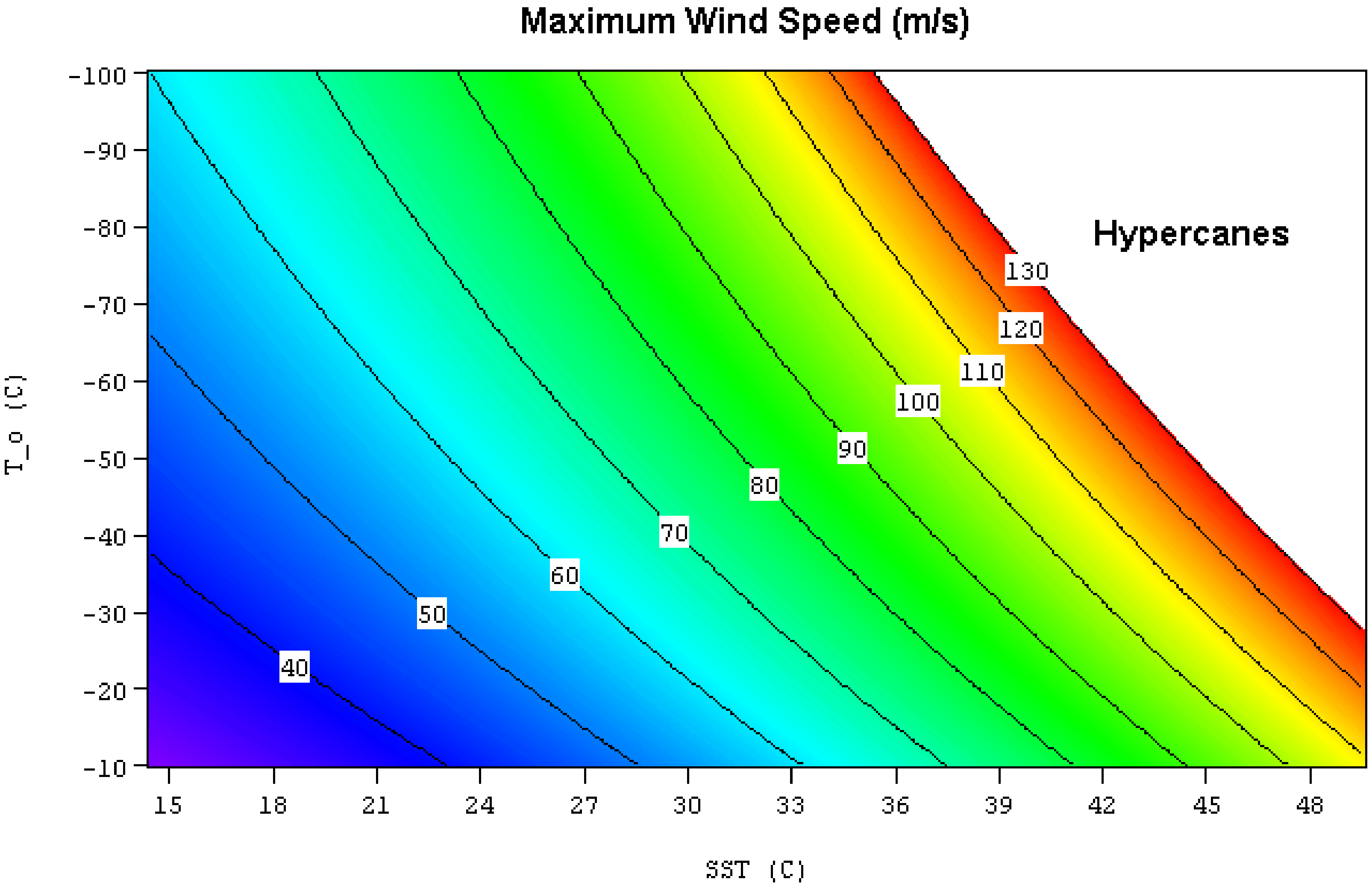
Theoretical Upper Bound on Hurricane Maximum Wind Speed:

Surface temperature

$$|V_{pot}|^2 \cong \boxed{\frac{C_k}{C_D}} \frac{T_s - T_o}{T_o} \underbrace{\left(k_0^* - k \right)}_{\text{Air-sea enthalpy disequilibrium}}$$

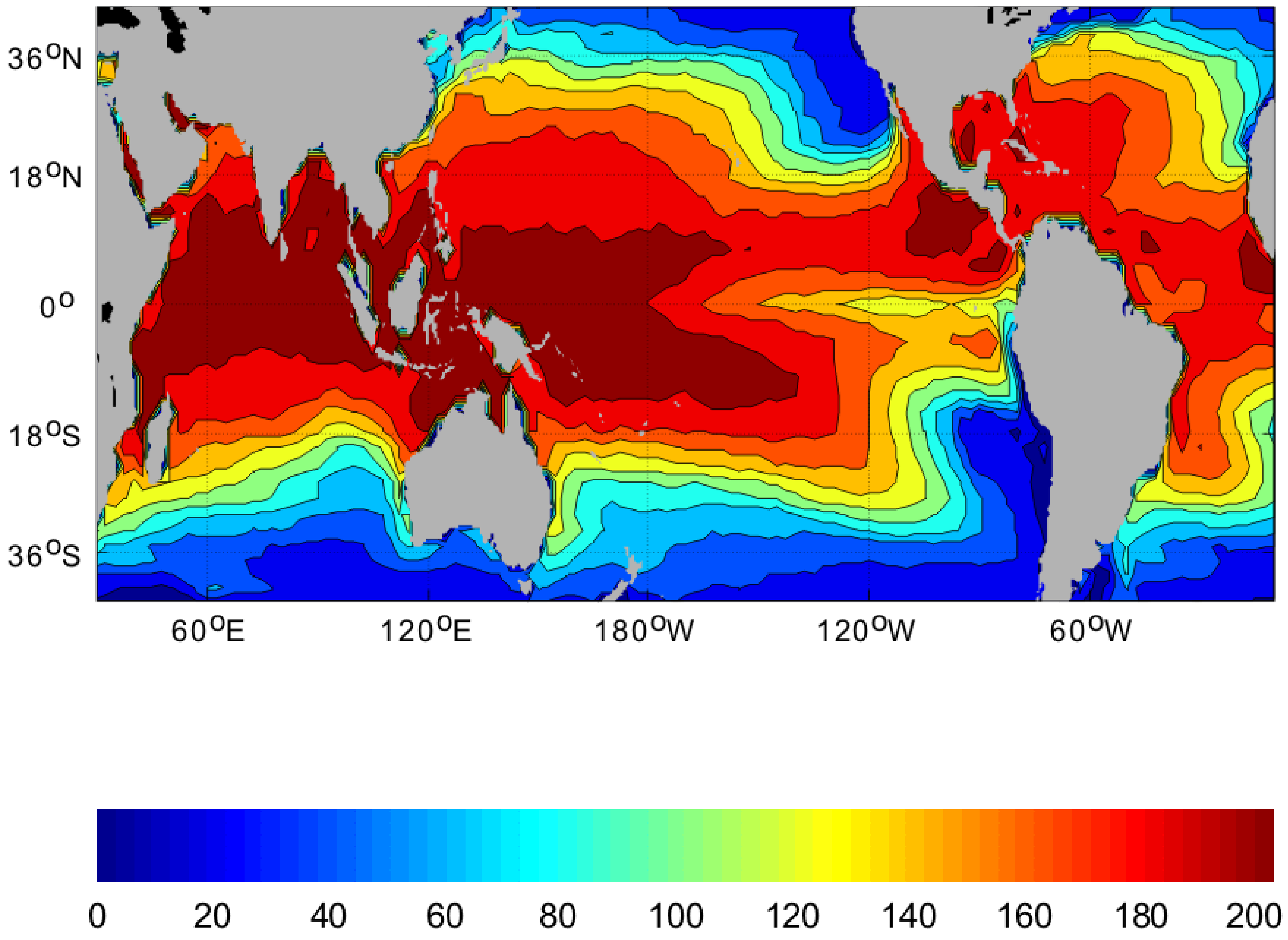
Ratio of exchange coefficients of enthalpy and momentum

Outflow temperature

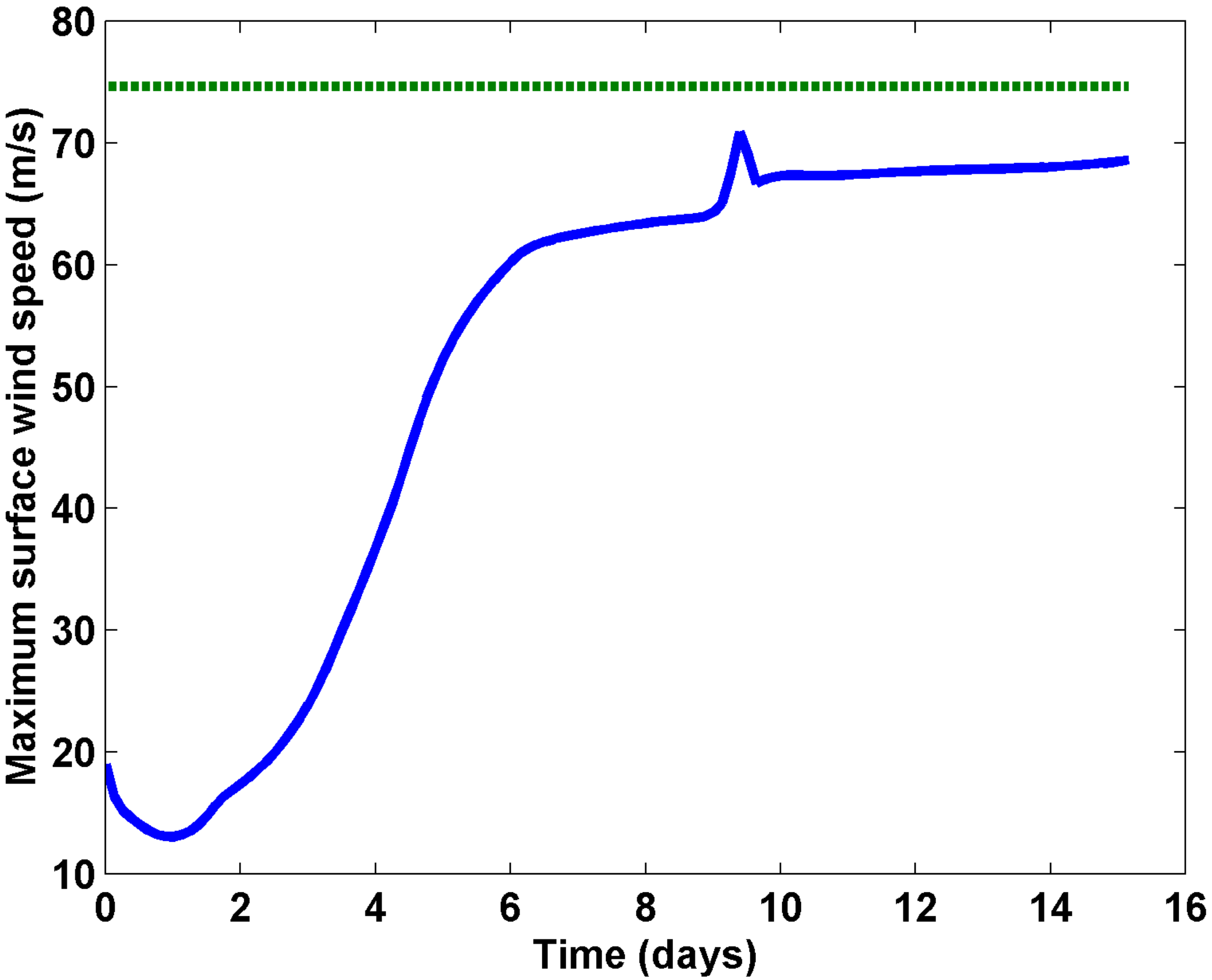


$\mathcal{H} = 0.75 \quad C_k/C_D = 1.2$

Maximum Annual Potential Intensity (MPH)



Numerical simulations



Thermodynamic disequilibrium necessary to maintain ocean heat balance:

Ocean mixed layer Energy Balance (neglecting lateral heat transport):

$$C_k \rho |\mathbf{V}_s| \left(k_0^* - k \right) = F_\downarrow - F_\uparrow - F_{entrain}$$

Ocean mixed layer entrainment

$$\rightarrow$$

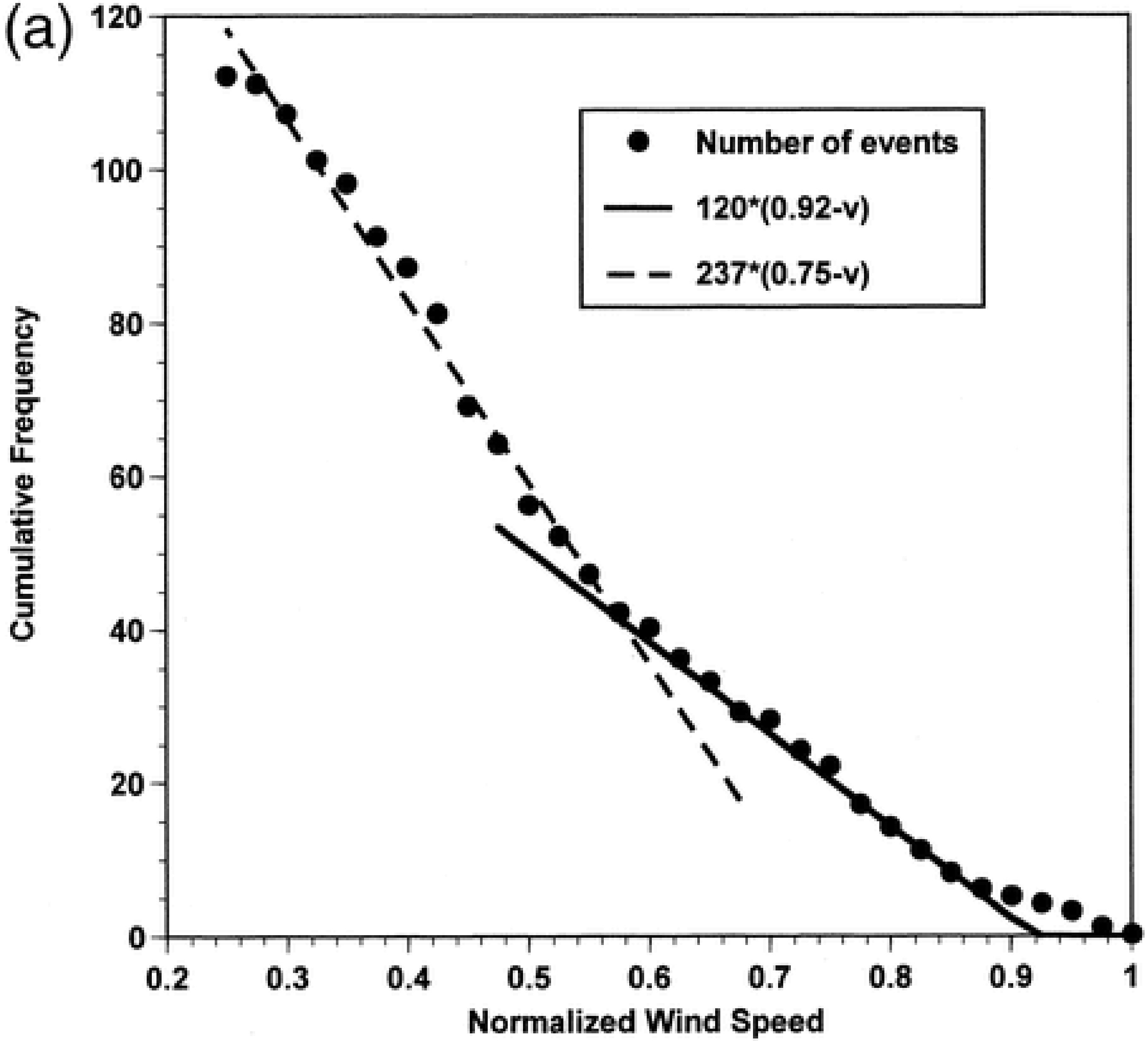
Greenhouse effect

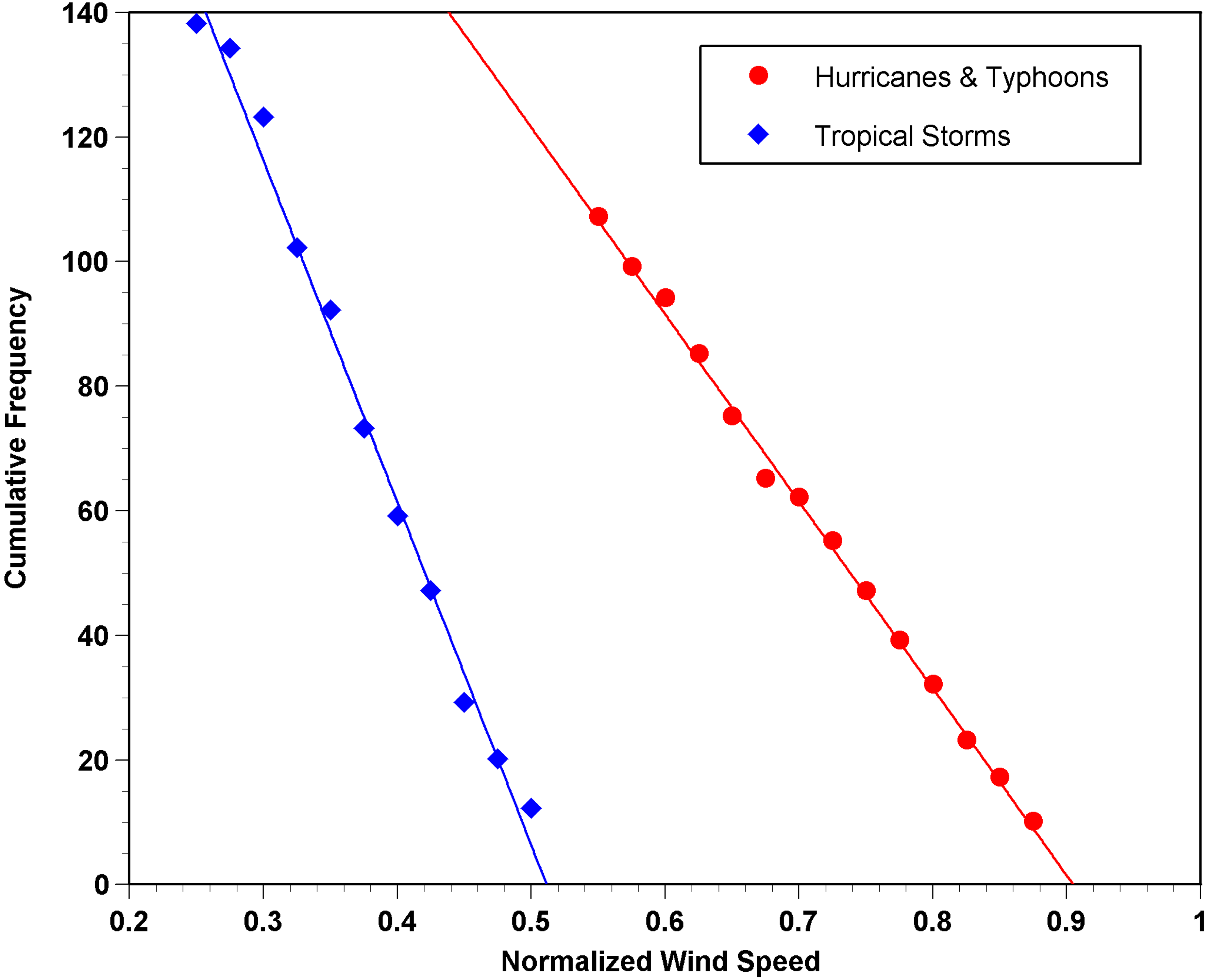
$$V_{pot}^2 = \frac{T_s - T_o}{T_o} \frac{F_\downarrow - F_\uparrow - F_{entrain}}{C_D \rho |\mathbf{V}_s|}$$

Weak explicit dependence on T_s

Mean surface wind speed

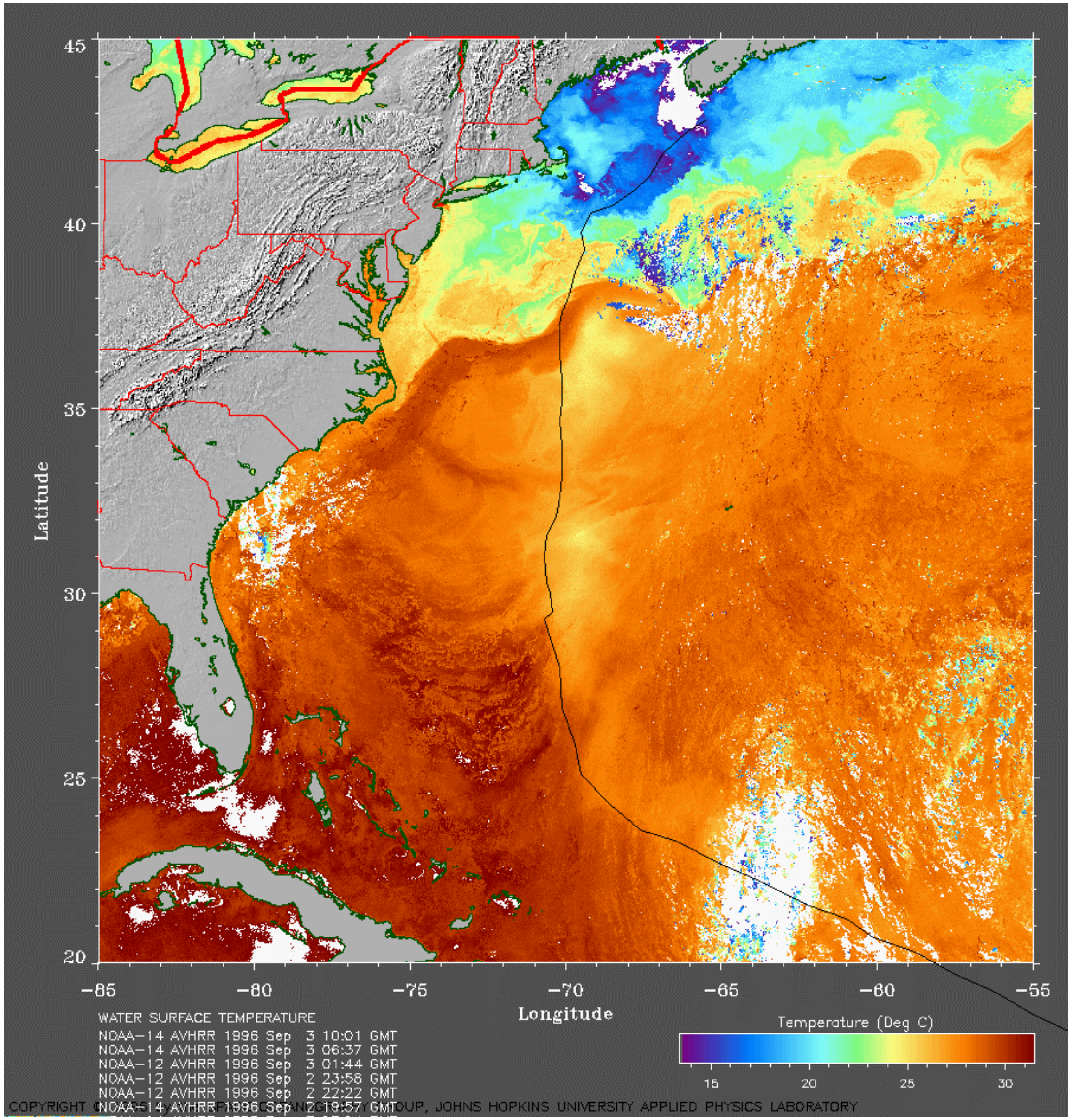
Relationship between potential intensity (PI) and intensity of real tropical cyclones


(a)
Cumulative Frequency
Normalized Wind Speed
Number of events
120*(0.92-v)
237*(0.75-v)
0
20
40
60
80
100
120
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

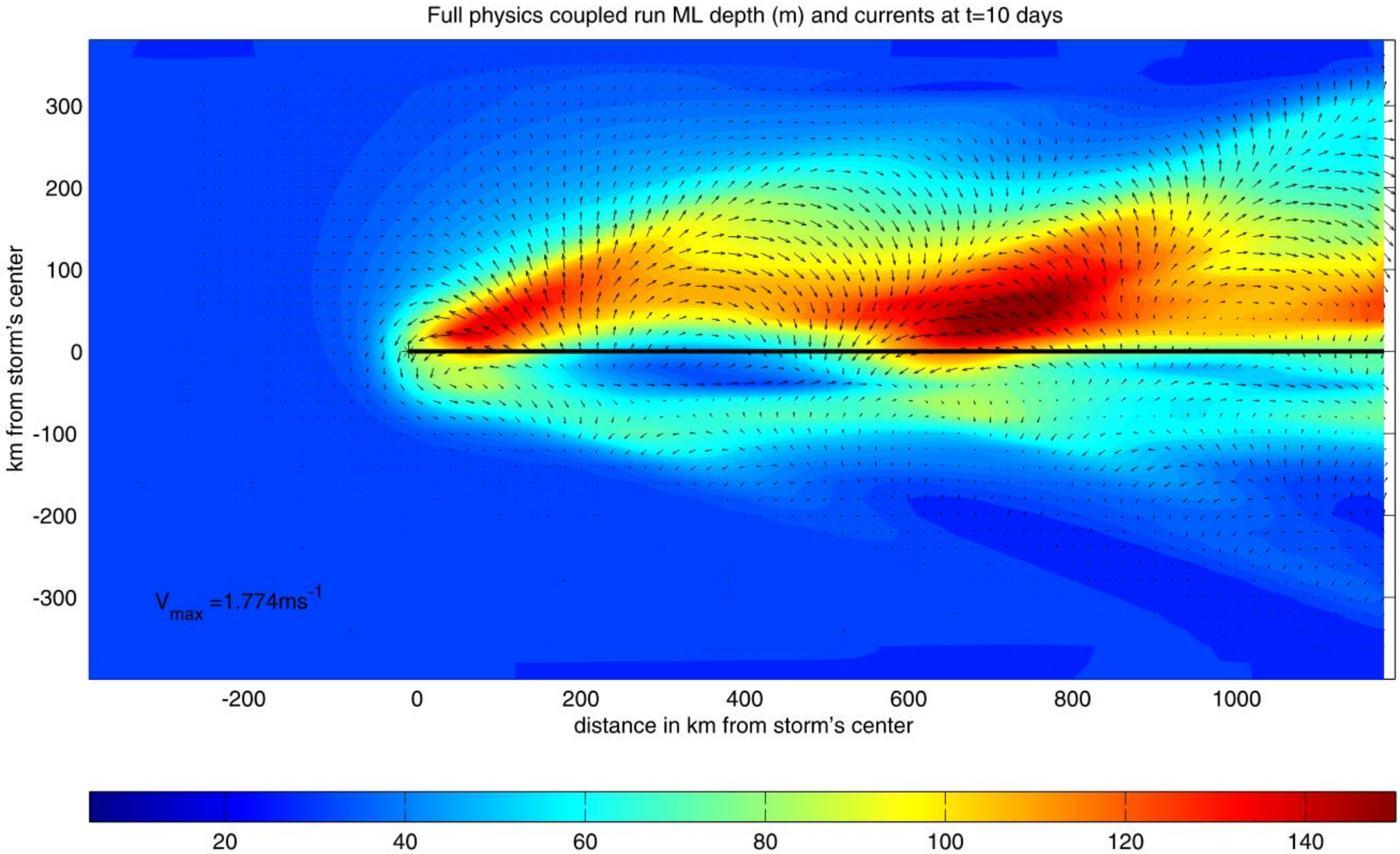

Hurricanes & Typhoons
Tropical Storms
Cumulative Frequency
Normalized Wind Speed
0
20
40
60
80
100
120
140
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Why do real storms seldom reach their thermodynamic potential?

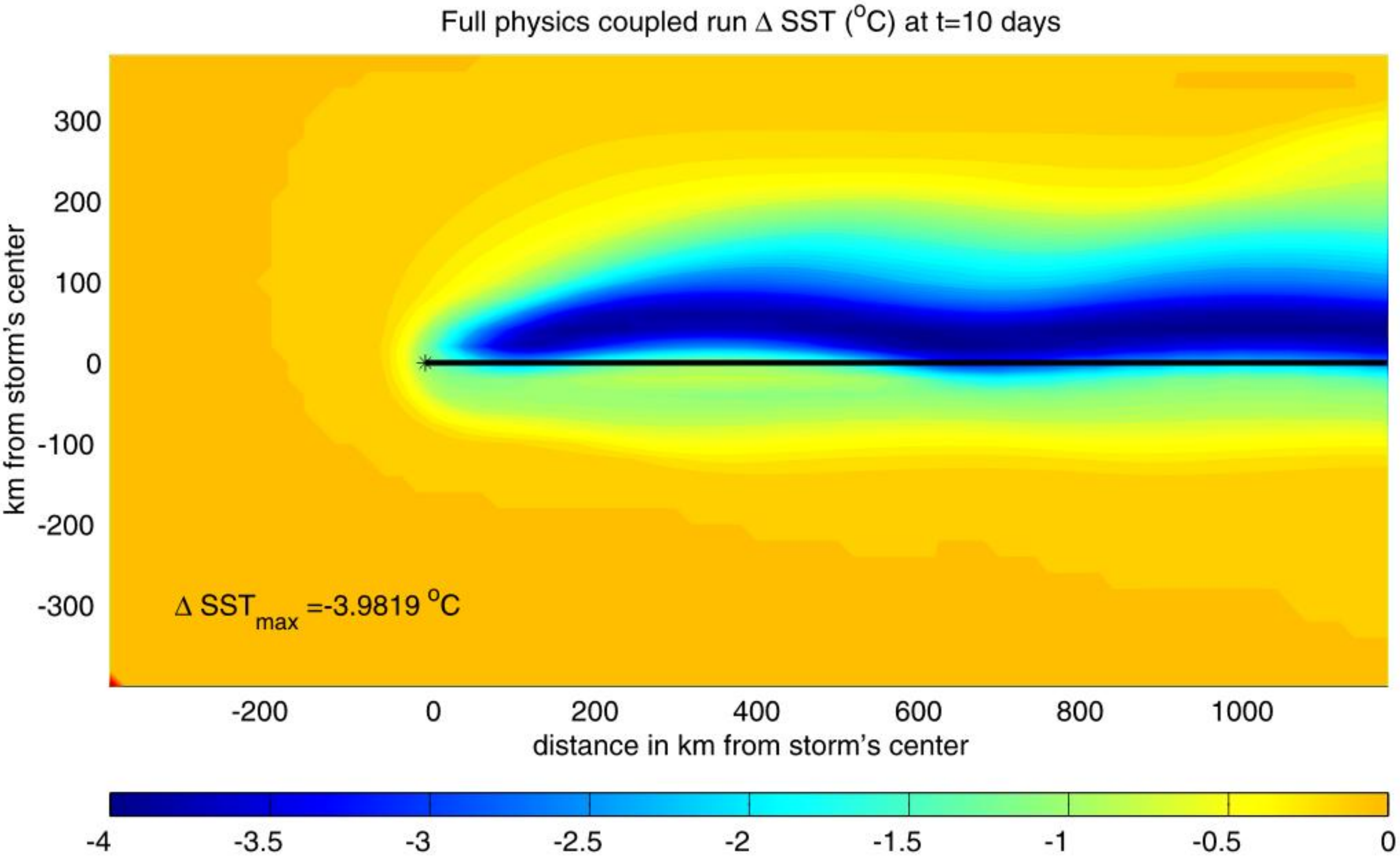
One Reason: Ocean Interaction


45
40
35
30
25
20
Latitude
−85
−80
−75
−70
−65
−60
−55
Longitude
WATER SURFACE TEMPERATURE
NOAA−14 AVHRR 1996 Sep 3 10:01 GMT
NOAA−14 AVHRR 1996 Sep 3 06:37 GMT
NOAA−12 AVHRR 1996 Sep 3 01:44 GMT
NOAA−12 AVHRR 1996 Sep 2 23:58 GMT
NOAA−12 AVHRR 1996 Sep 2 22:22 GMT
NOAA−14 AVHRR 1996 Sep 2 19:57 GMT
Temperature (Deg C)
15
20
25
30
COPYRIGHT [illegible] GROUP, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

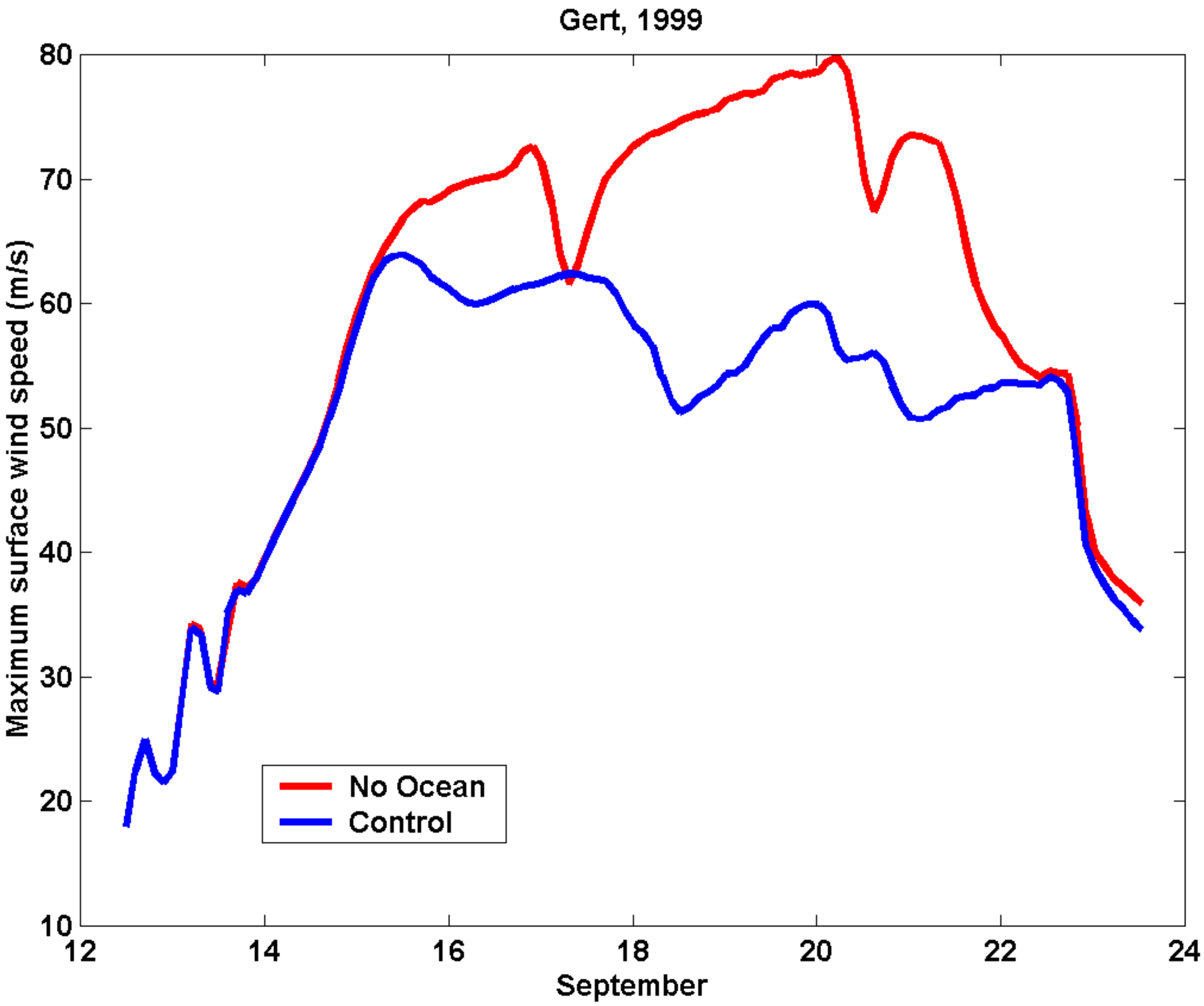
Mixed layer depth and currents



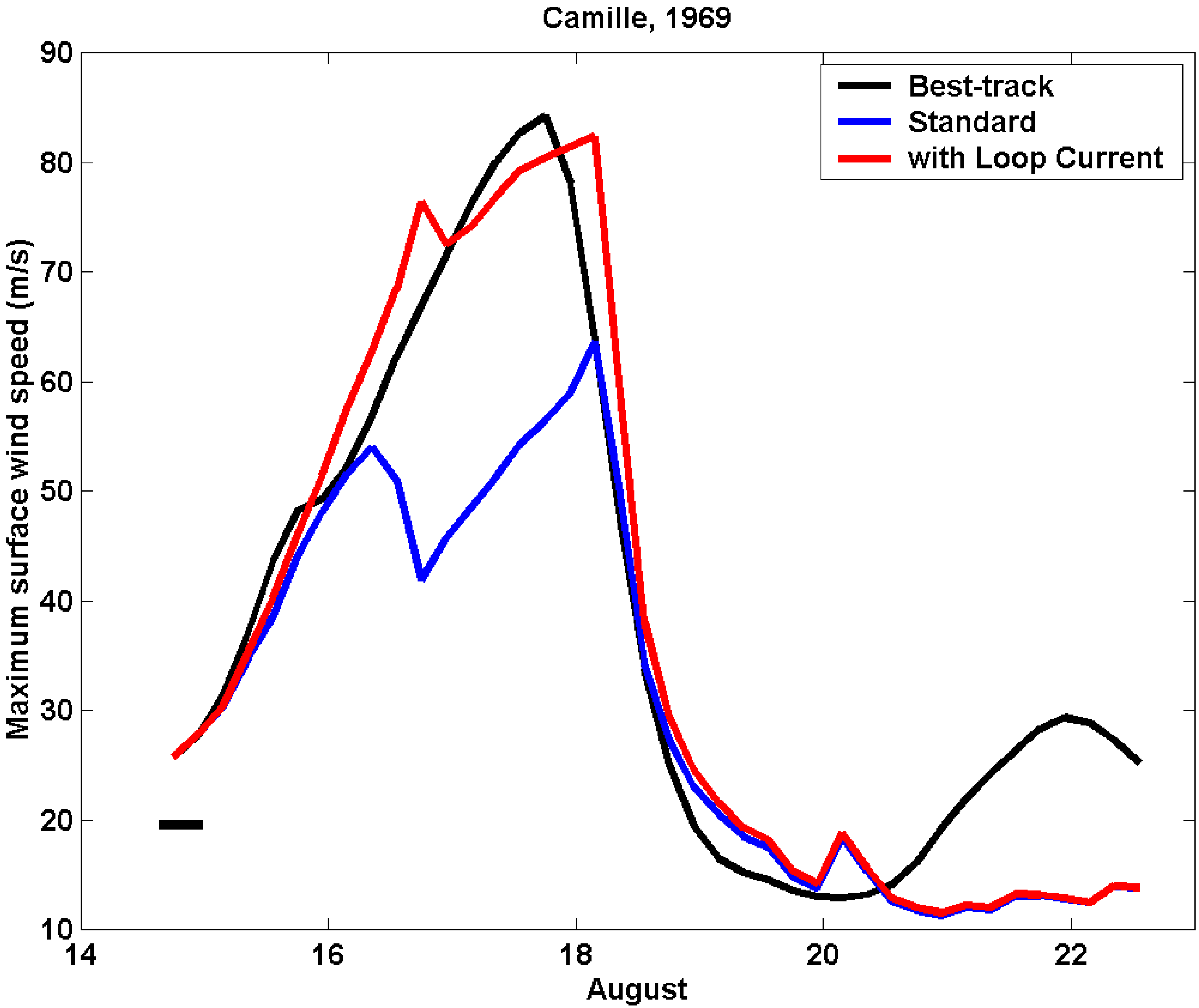
SST Change

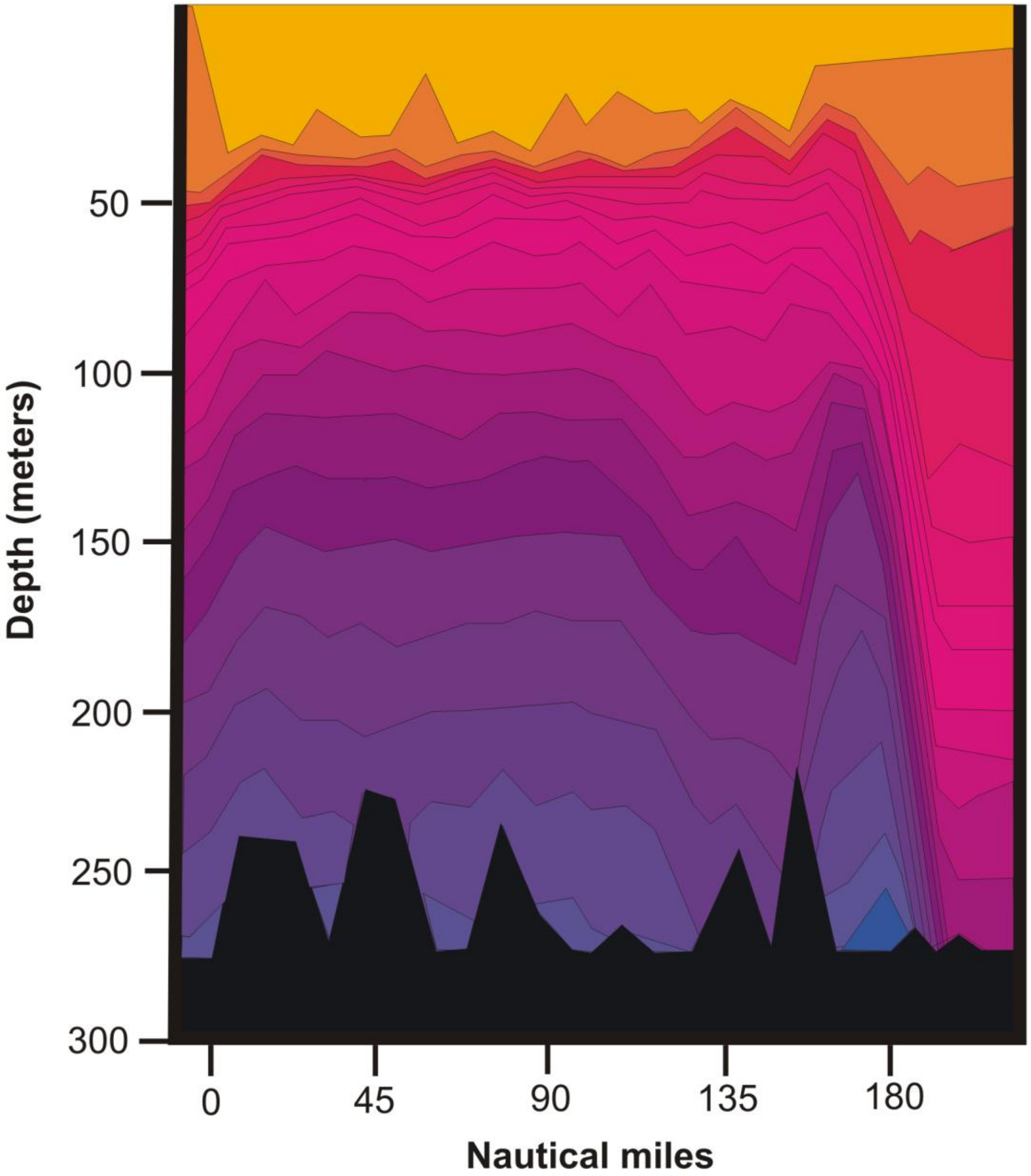

Full physics coupled run Δ SST (°C) at t=10 days
300
200
100
0
-100
-200
-300
km from storm's center
Δ SST max =-3.9819 °C
-200
0
200
400
600
800
1000
distance in km from storm's center
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0

Comparing Fixed to Interactive SST:

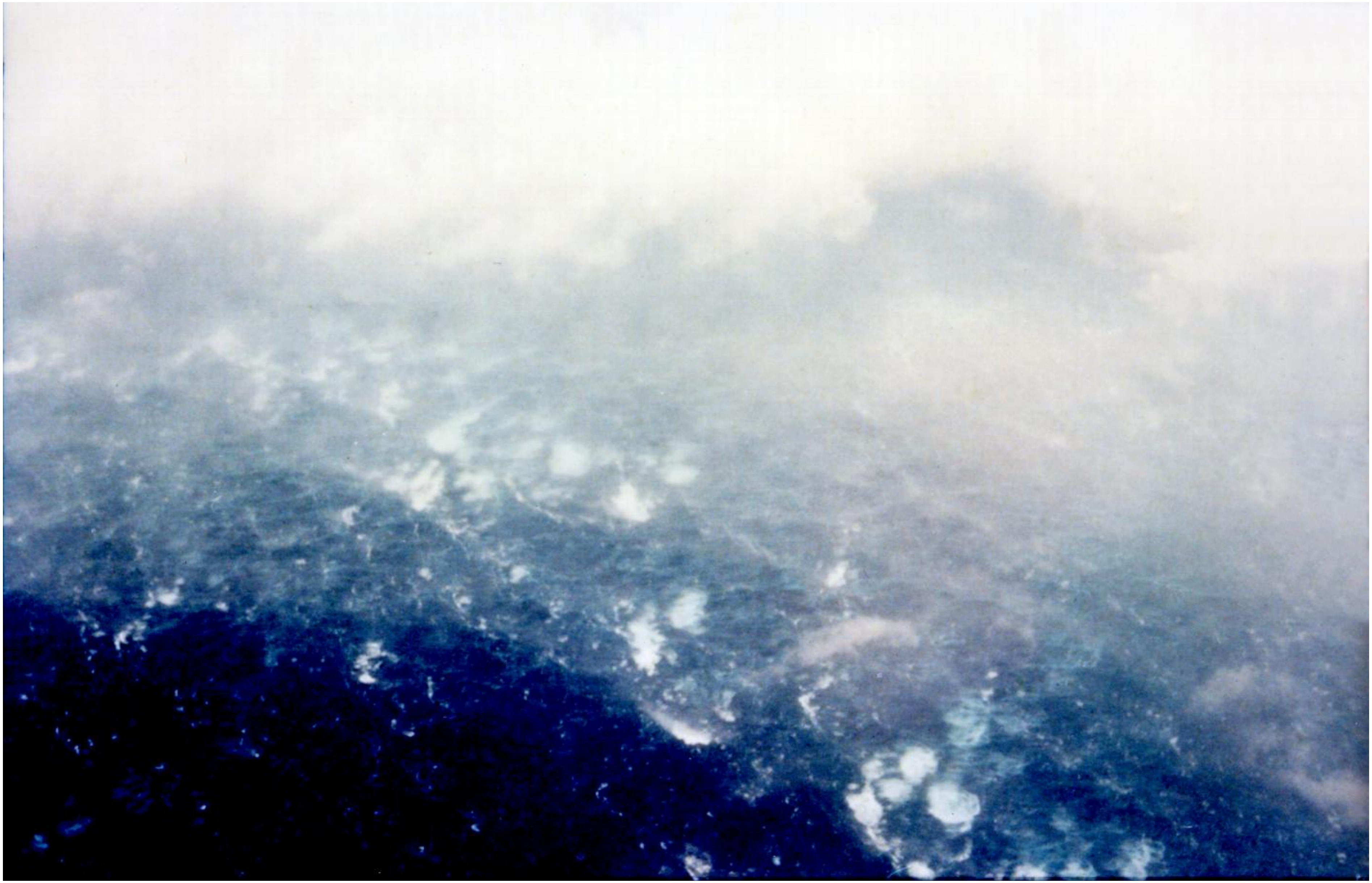


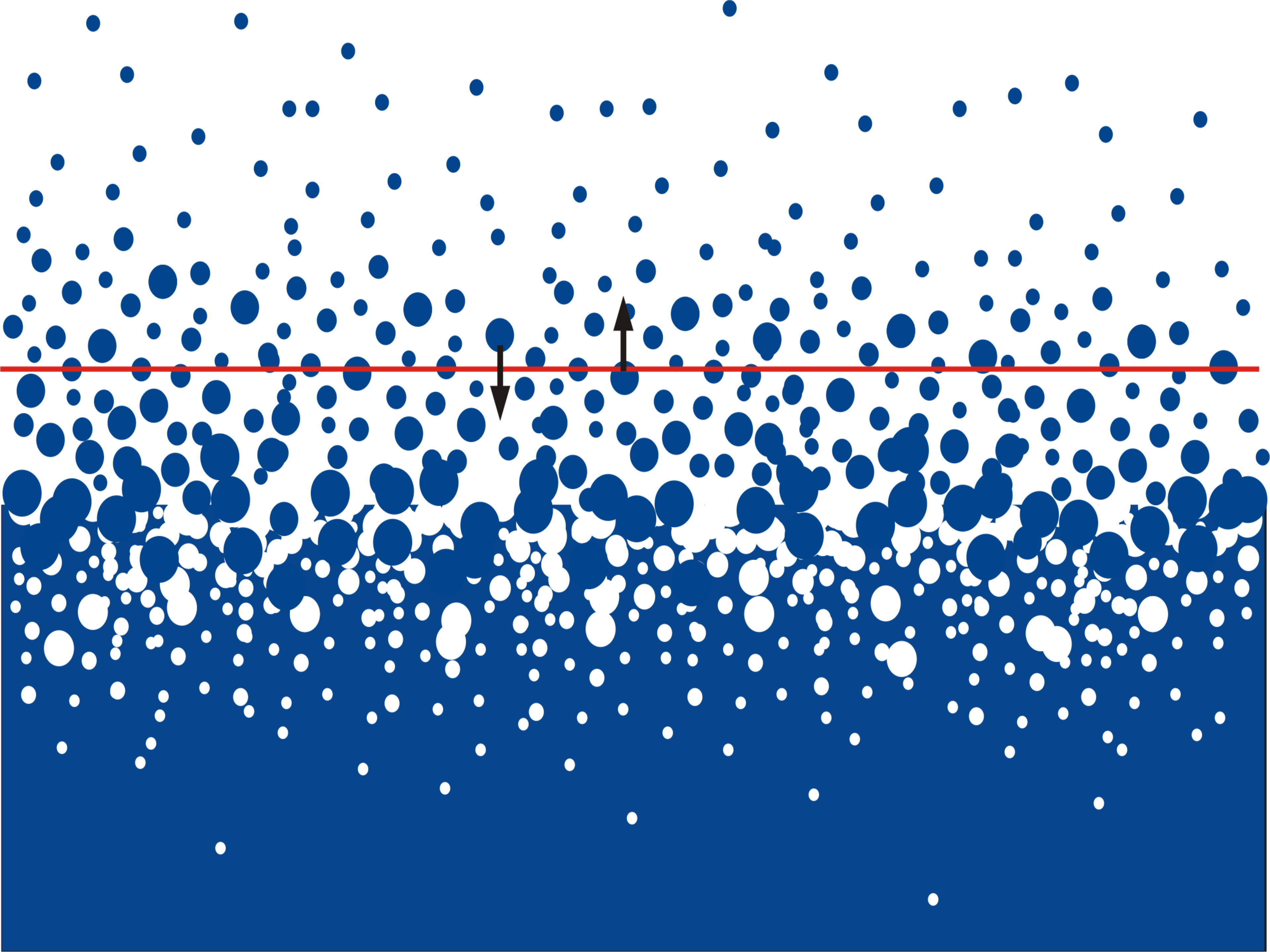
A good simulation of Camille can only be obtained by assuming that it traveled right up the axis of the Loop Current:



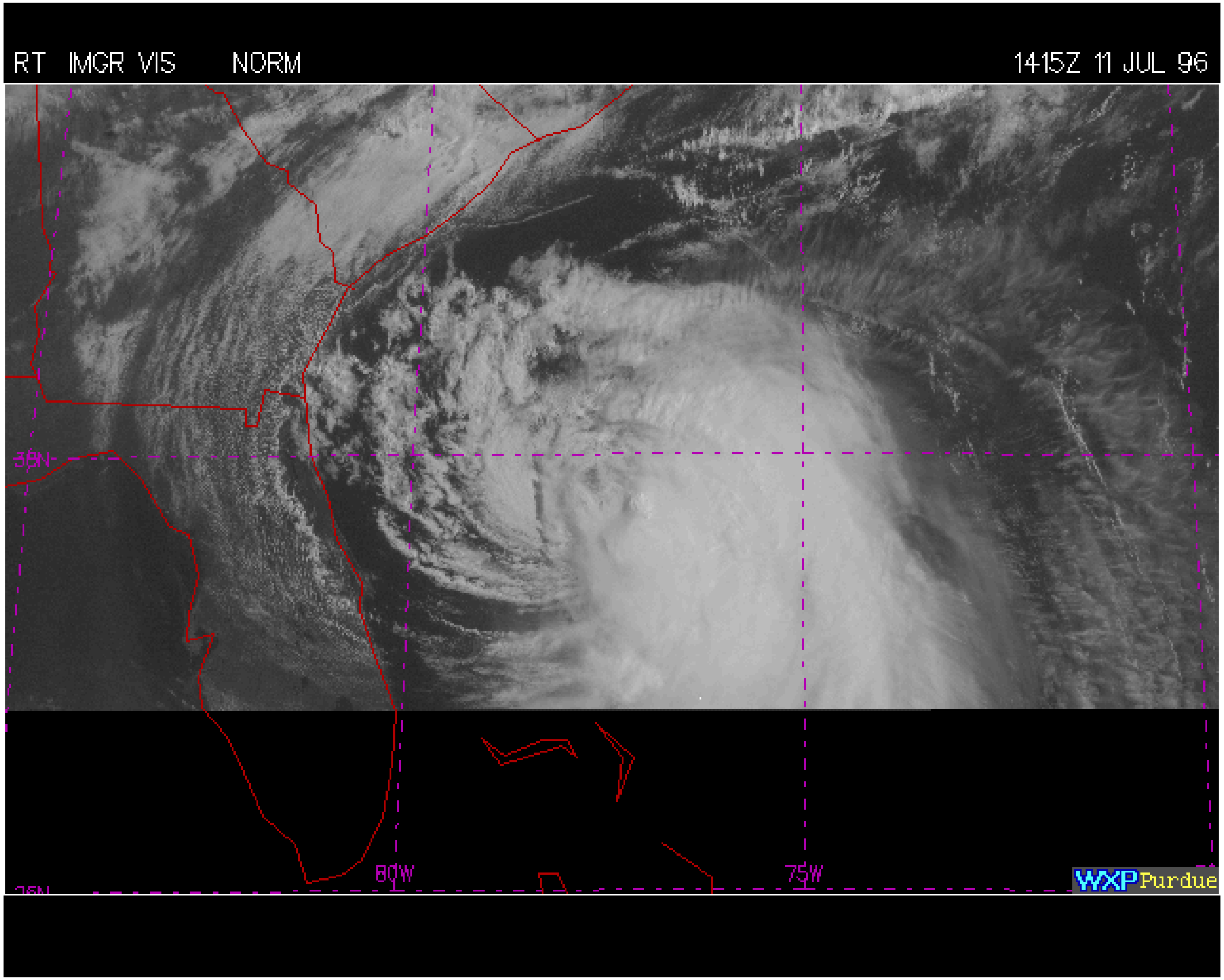

Depth (meters)
50
100
150
200
250
300
0
45
90
135
180
Nautical miles

2. Sea Spray

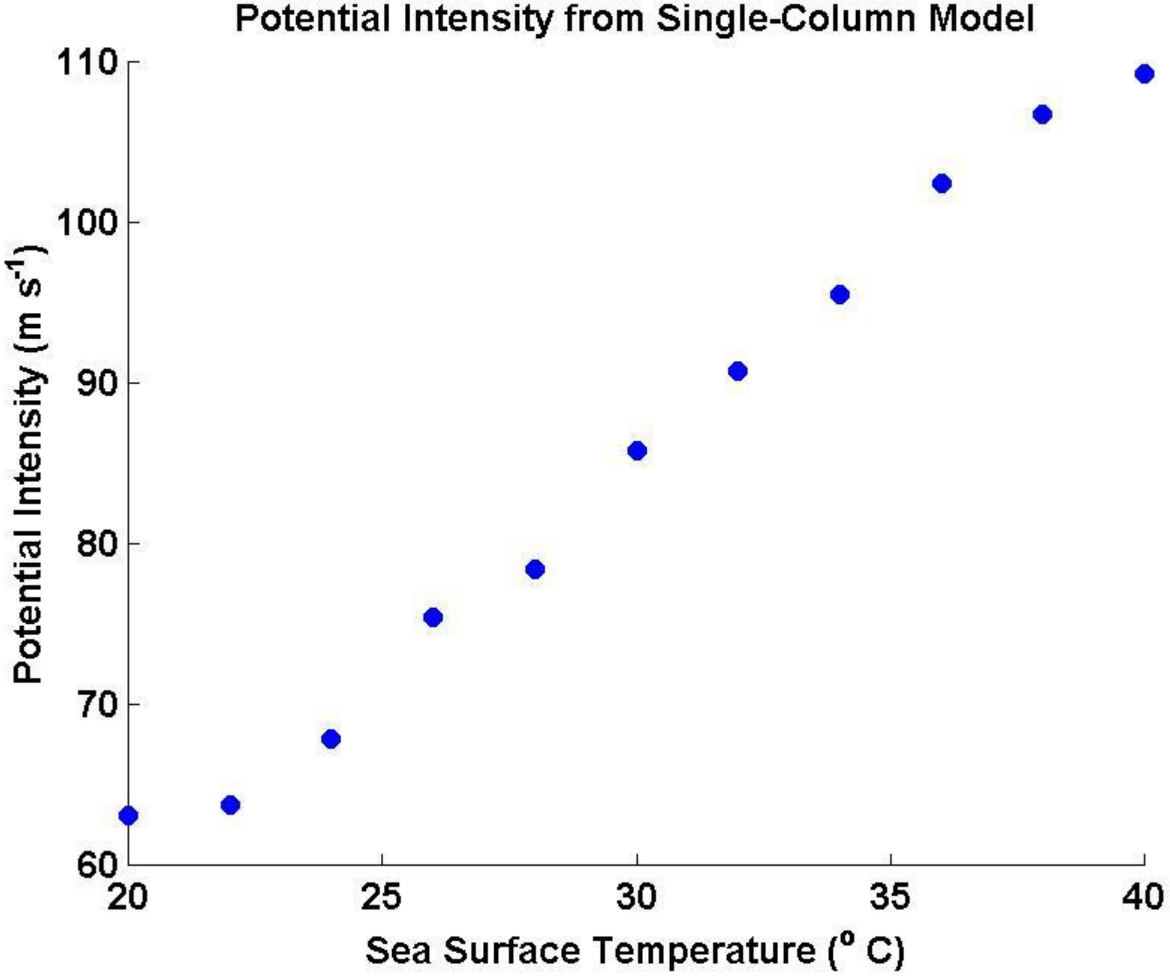




3. Wind Shear



Dependence on Sea Surface Temperature (SST):



What controls global tropical cyclone frequency?

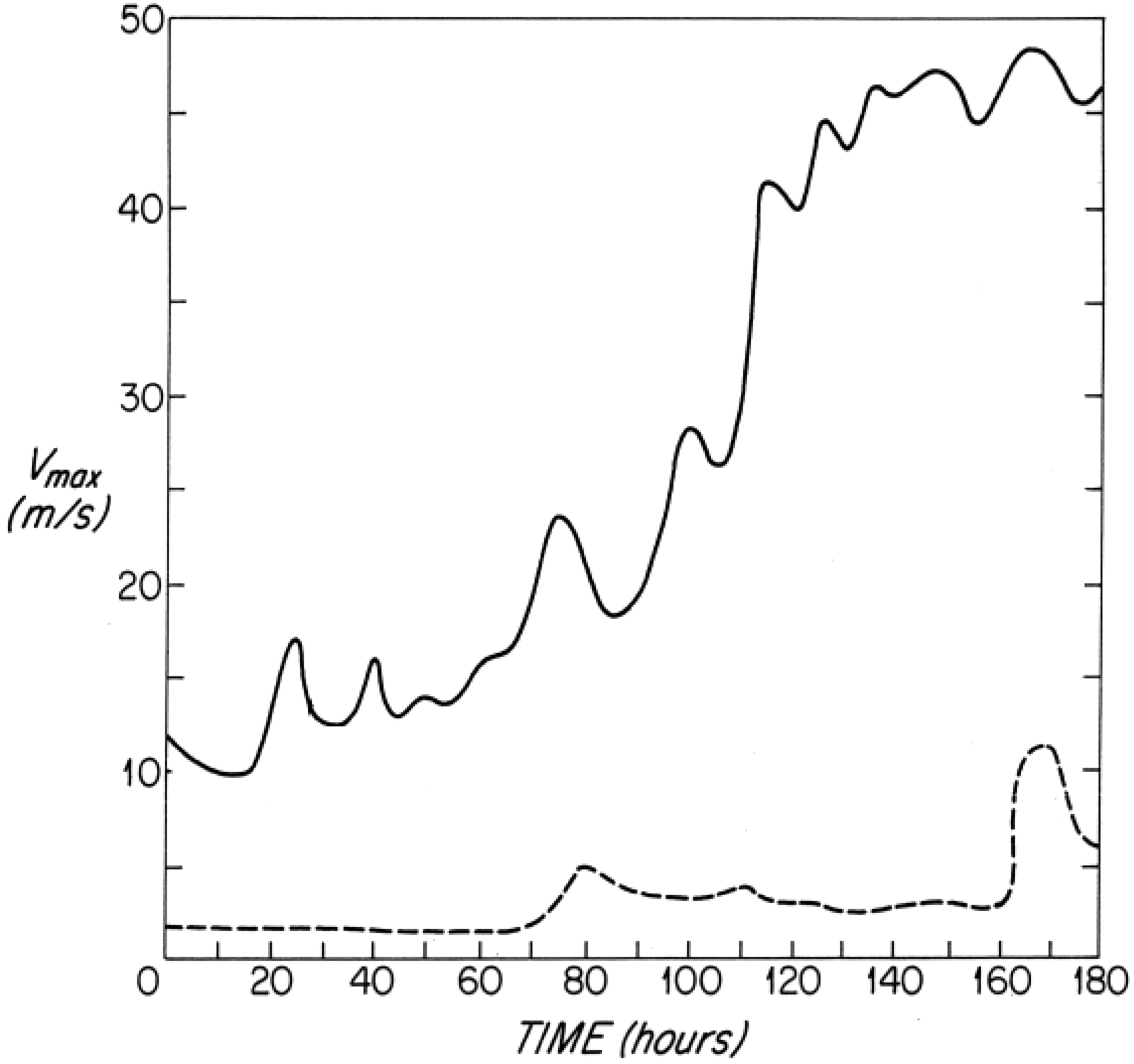
- In today’s climate, tropical cyclones must be triggered by independent disturbances

- Tropical cyclone models also require finite amplitude perturbations to initiate hurricanes

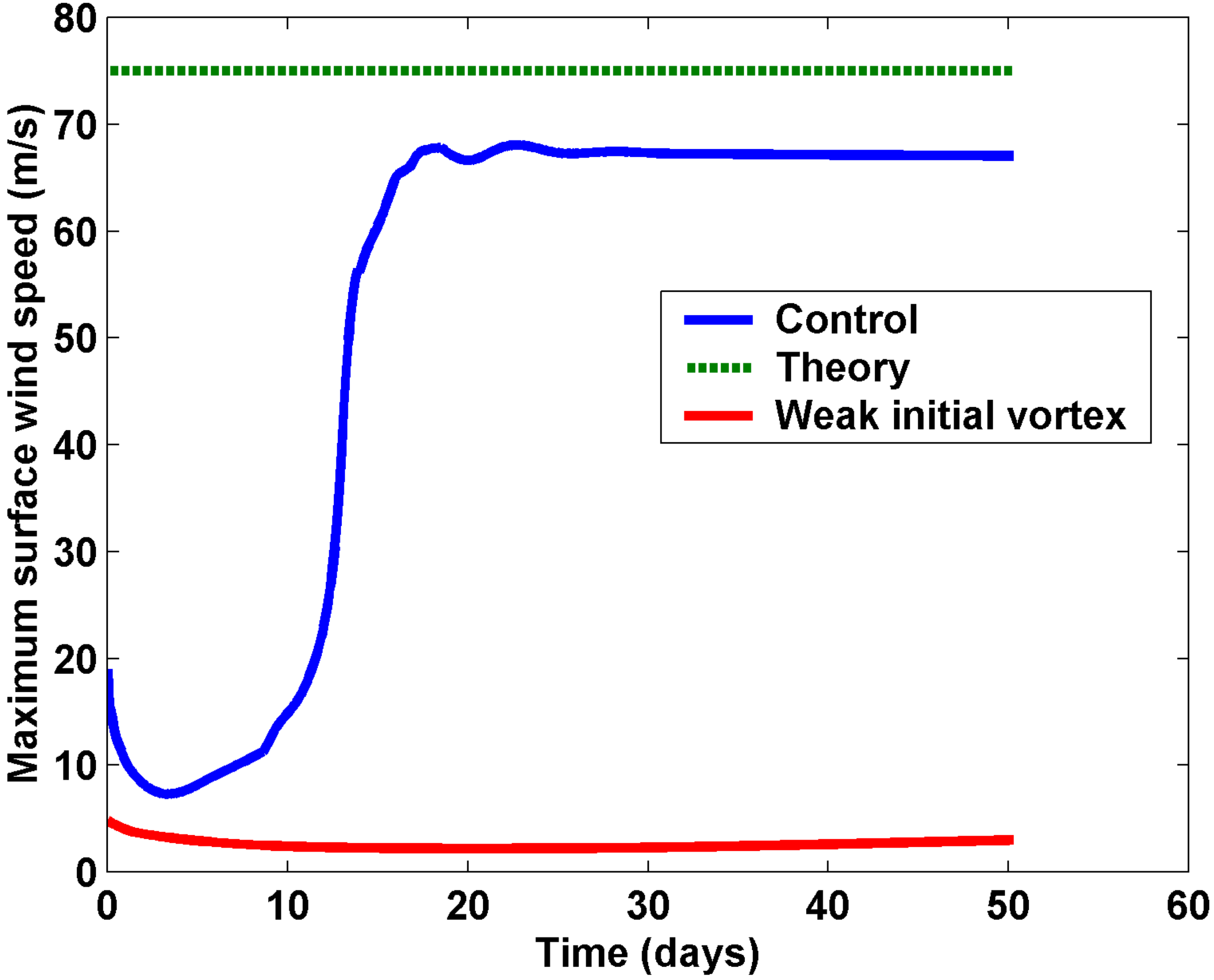
Numerical Simulations

Axisymmetric, nonhydrostatic, cloud-resolving model of Rotunno and Emanuel (*J. Atmos. Sci.*, 1987); see Emanuel and Rotunno, *Tellus*, 1989. 3.75 km horizontal resolution; 300 m in vertical

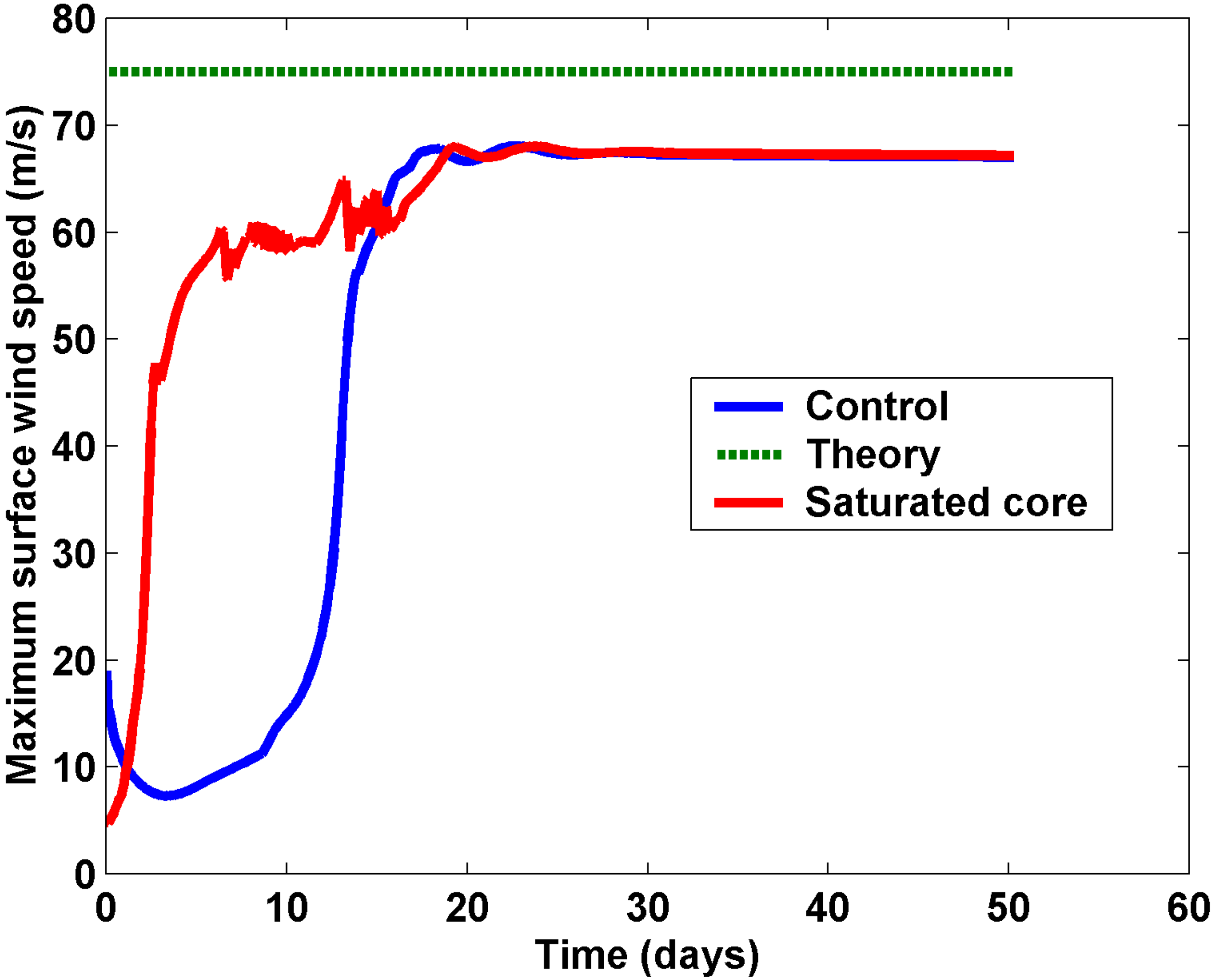
Classical initialization with warm-core vortex

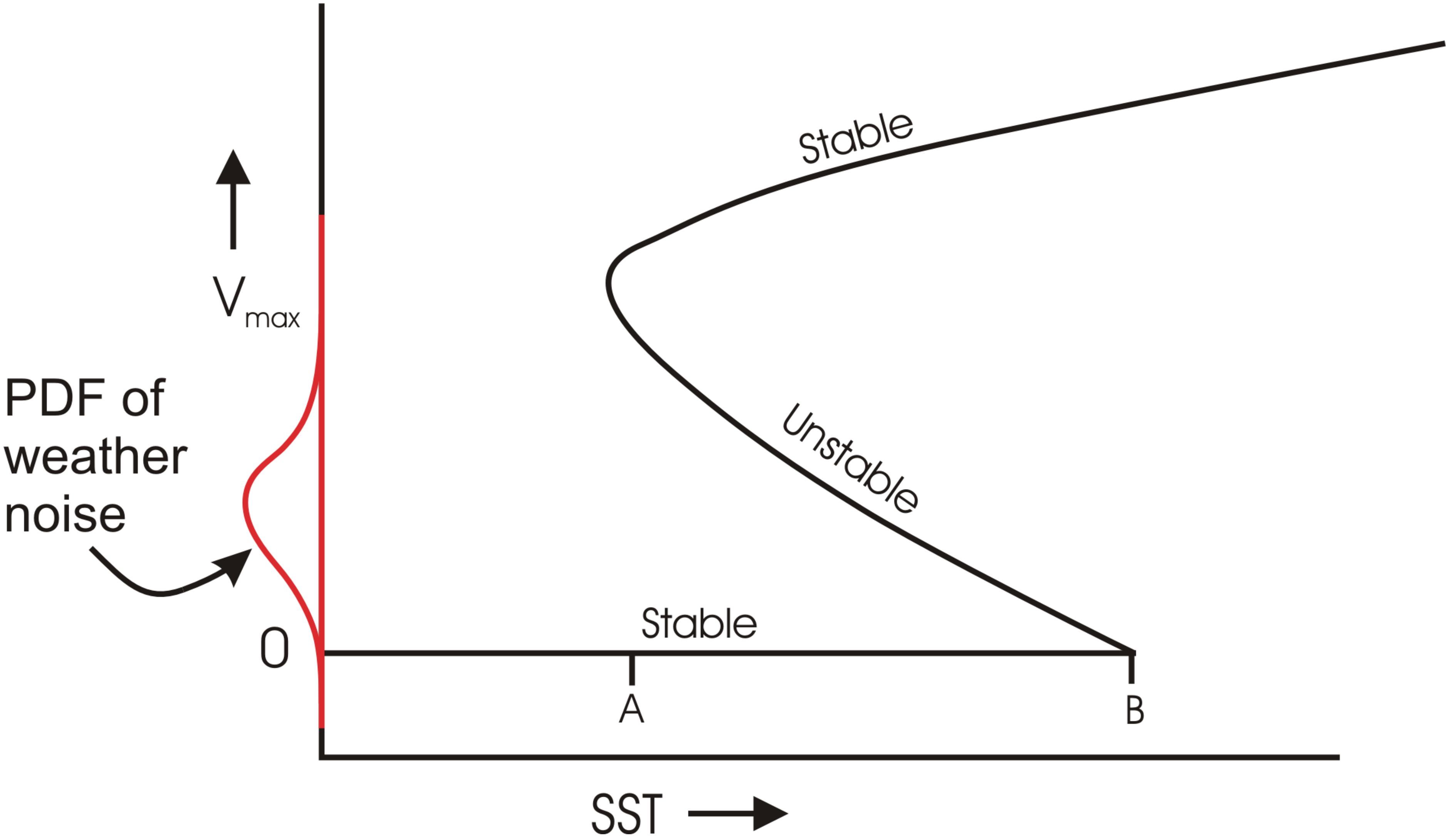


Same behavior in poor man’s model:

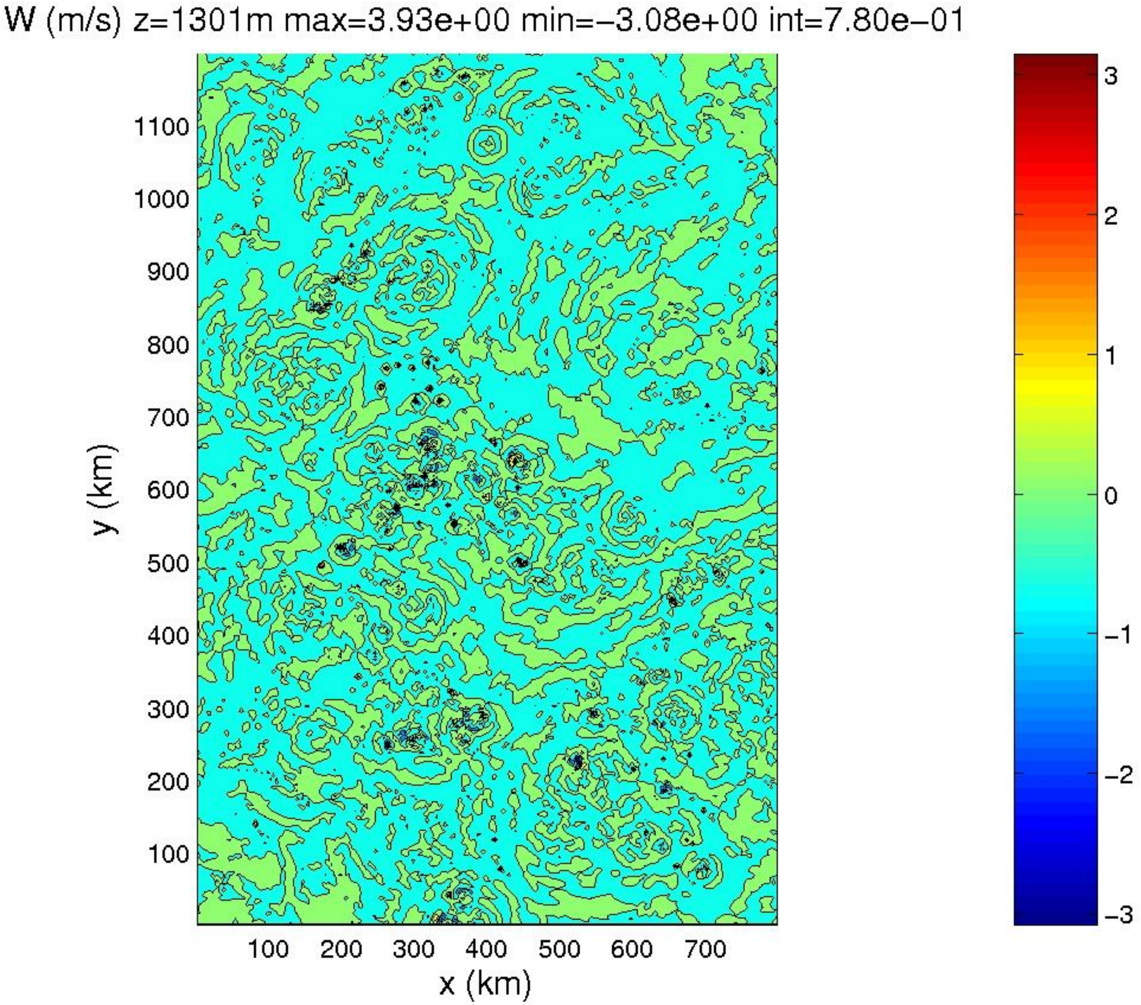


Saturate troposphere inside 100 km in initial state:



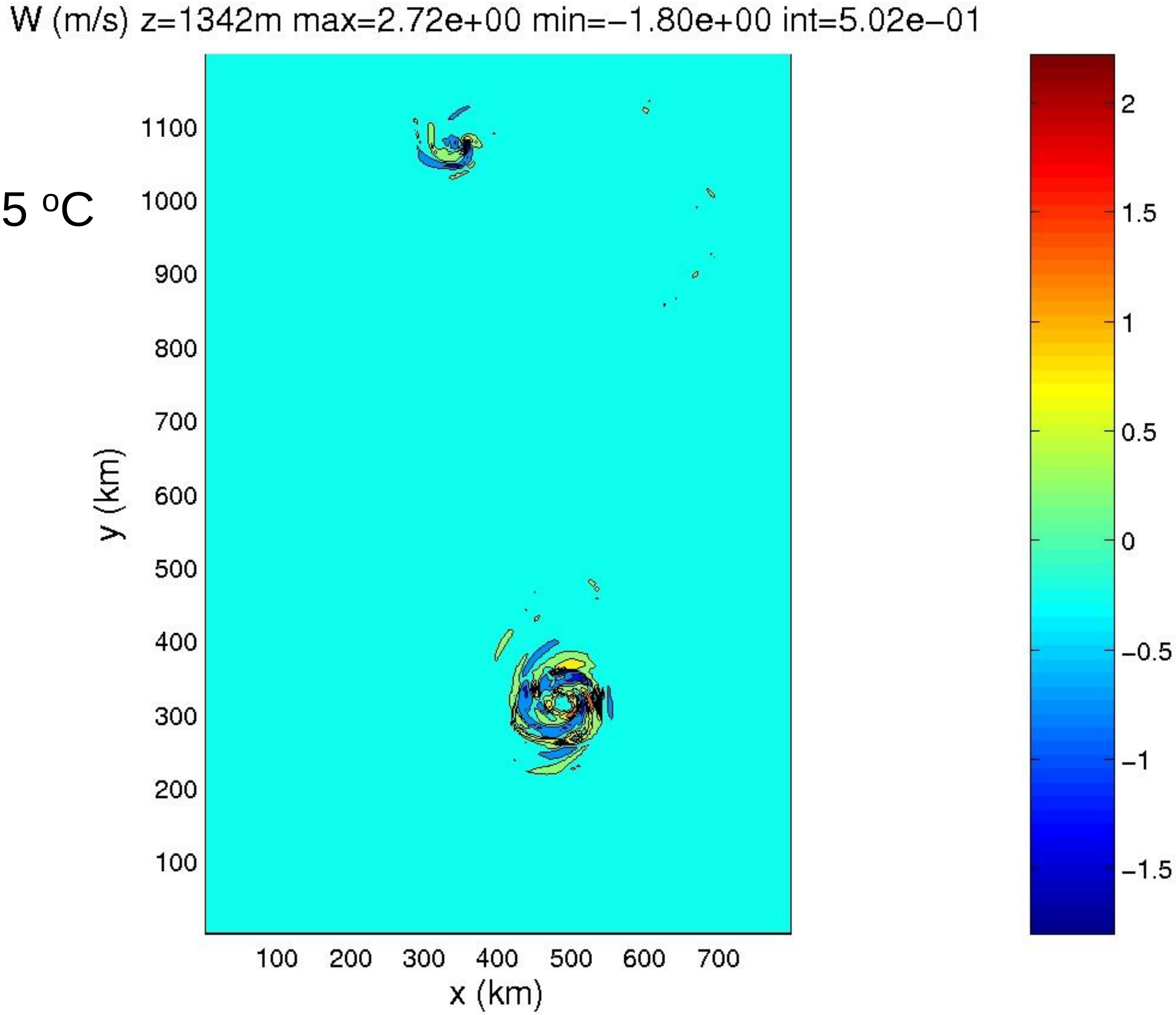

Stable
PDF of weather noise
V_{max}
Unstable
Stable
0
A
B
SST

SST = 30 ^{o}C



Integrations of a 3-D cloud system-resolving model in radiative-convective equilibrium with fixed SST, by David Nolan

SST = 35 ^{o}C


W (m/s) z=1342m max=2.72e+00 min=−1.80e+00 int=5.02e−01
y (km)
1100
1000
900
800
700
600
500
400
300
200
100
x (km)
100
200
300
400
500
600
700
2
1.5
1
0.5
0
−0.5
−1
−1.5

Second Approach to Frequency Issue:

Develop an empirical index based on monthly re-analysis data

Test index against geographic, seasonal and interannual variability

Empirical Index:

$$I = \left|10^5\eta\right|^{3/2}\left(\frac{\mathcal{H}}{50}\right)^3\left(\frac{V_{pot}}{70}\right)^3\left(1+0.1V_{shear}\right)^{-2},$$

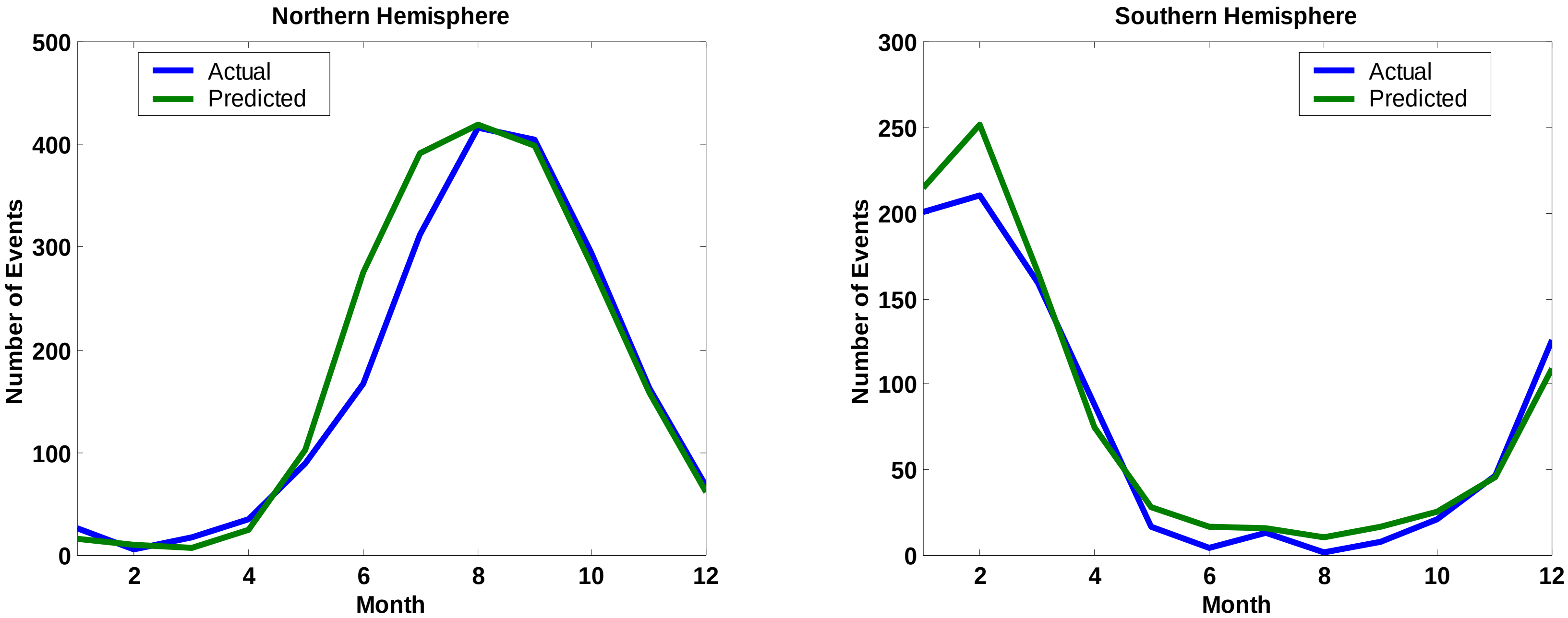
$$\eta \equiv 850\, hPa\ absolute\ vorticity\ (s^{-1}),$$

$$V_{pot} \equiv Potential\ wind\ speed\ (ms^{-1}),$$

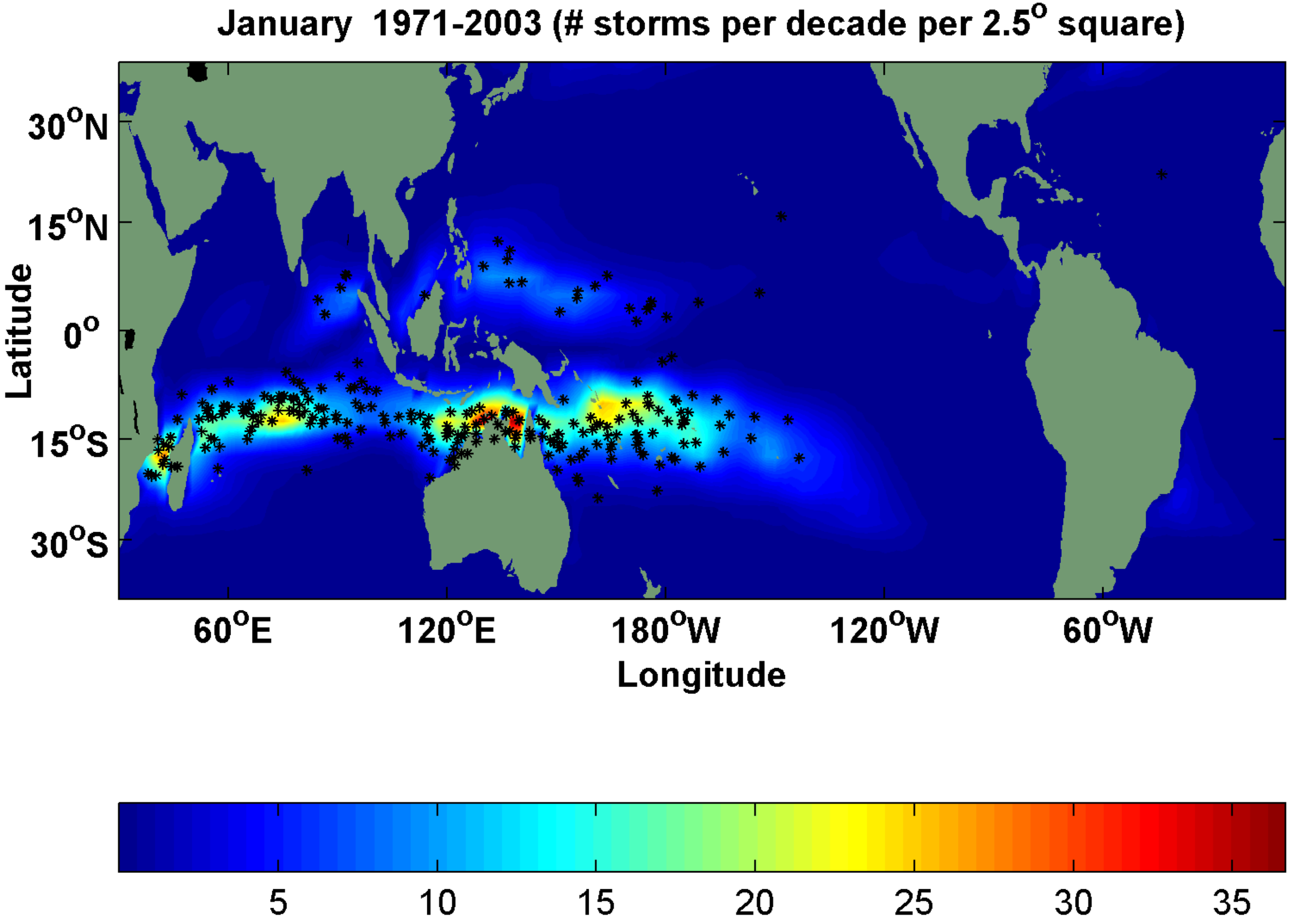
$$\mathcal{H} \equiv 600\, mb\ relative\ humidity\ (\%),$$

$$V_{shear} \equiv \left|\mathbf{V}_{850} - \mathbf{V}_{250}\right| \quad (ms^{-1}).$$

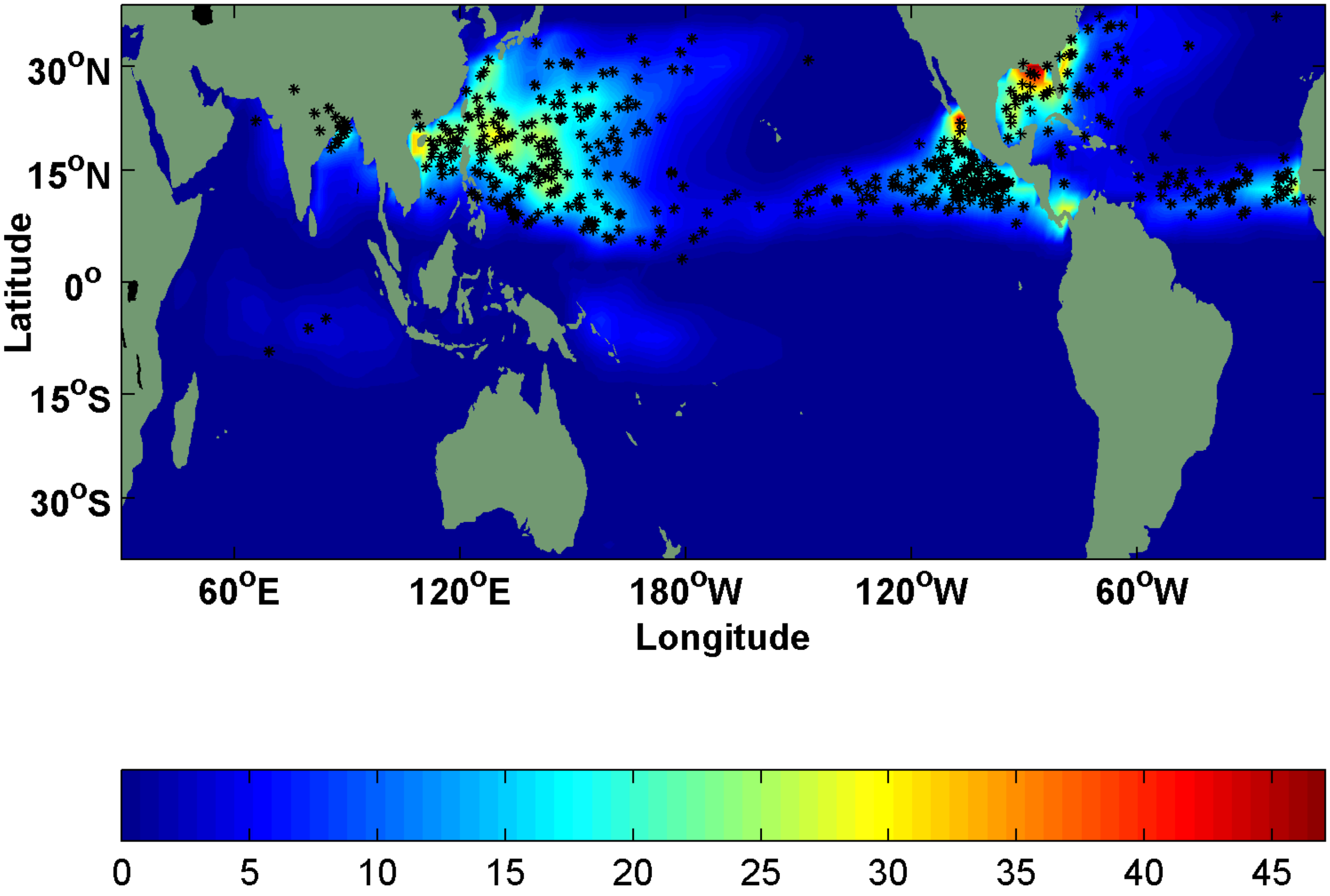
Seasonal Variability:



Spatial Variability:

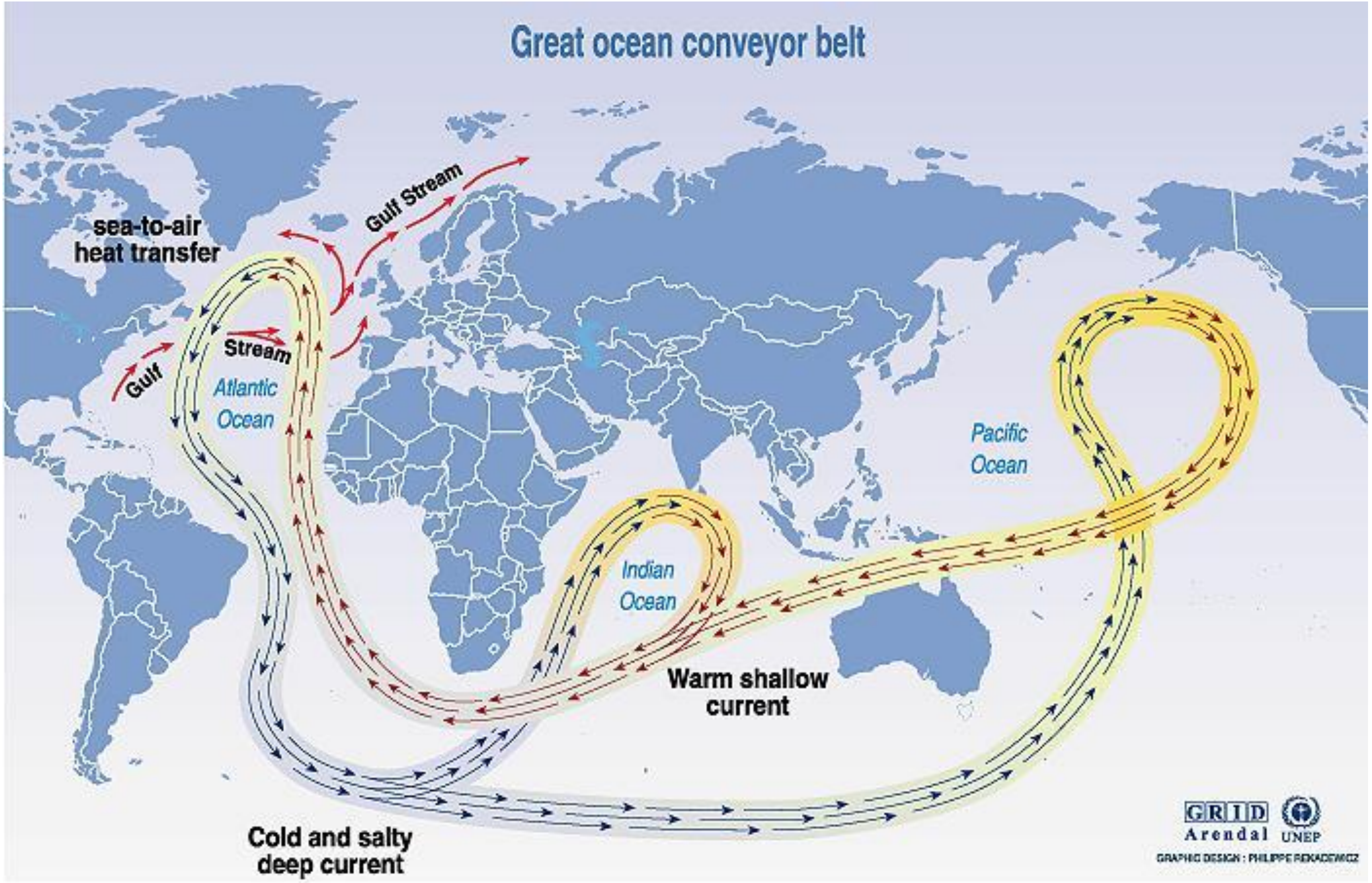


August 1971-2003 (# storms per decade per 2.5^{o} square)

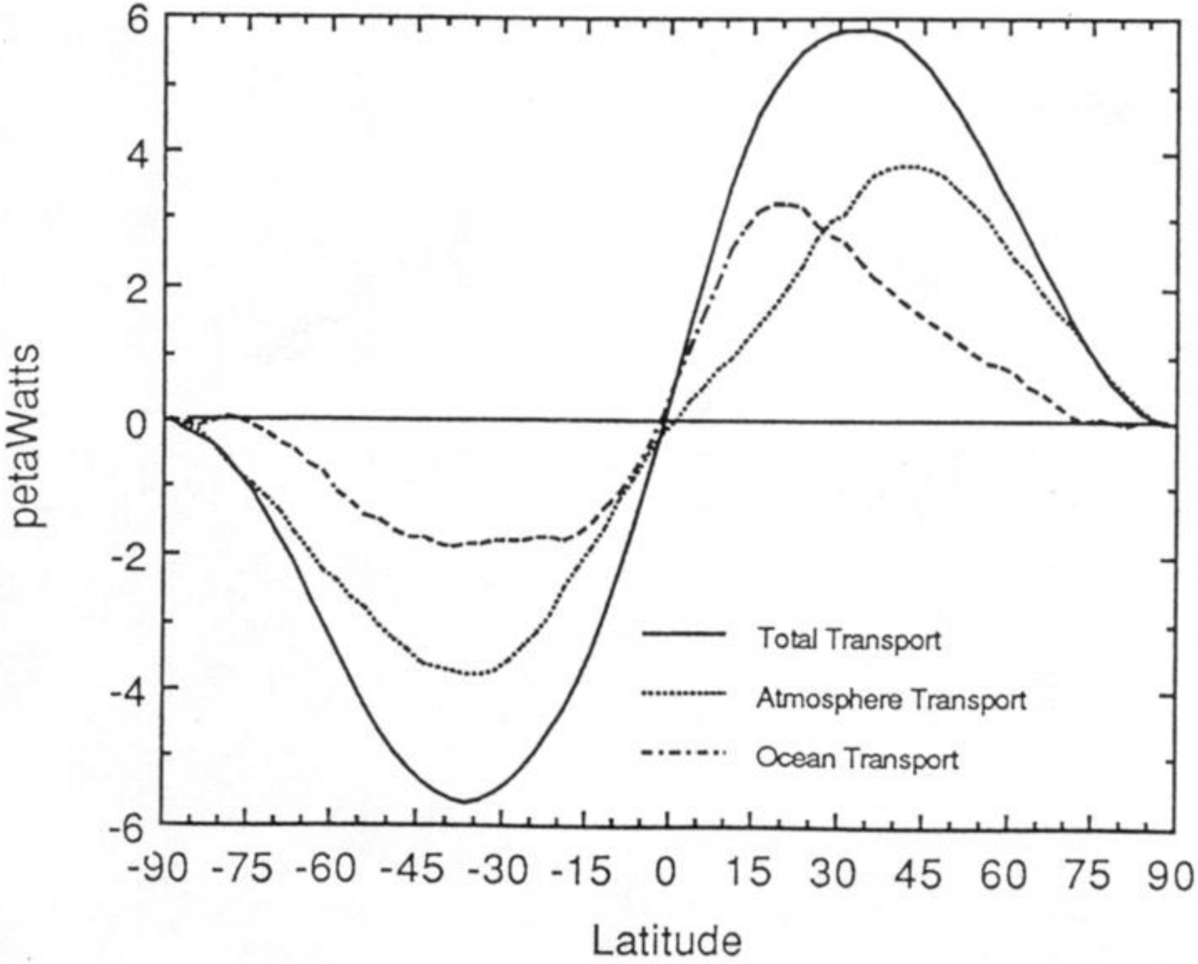


Ocean Feedback

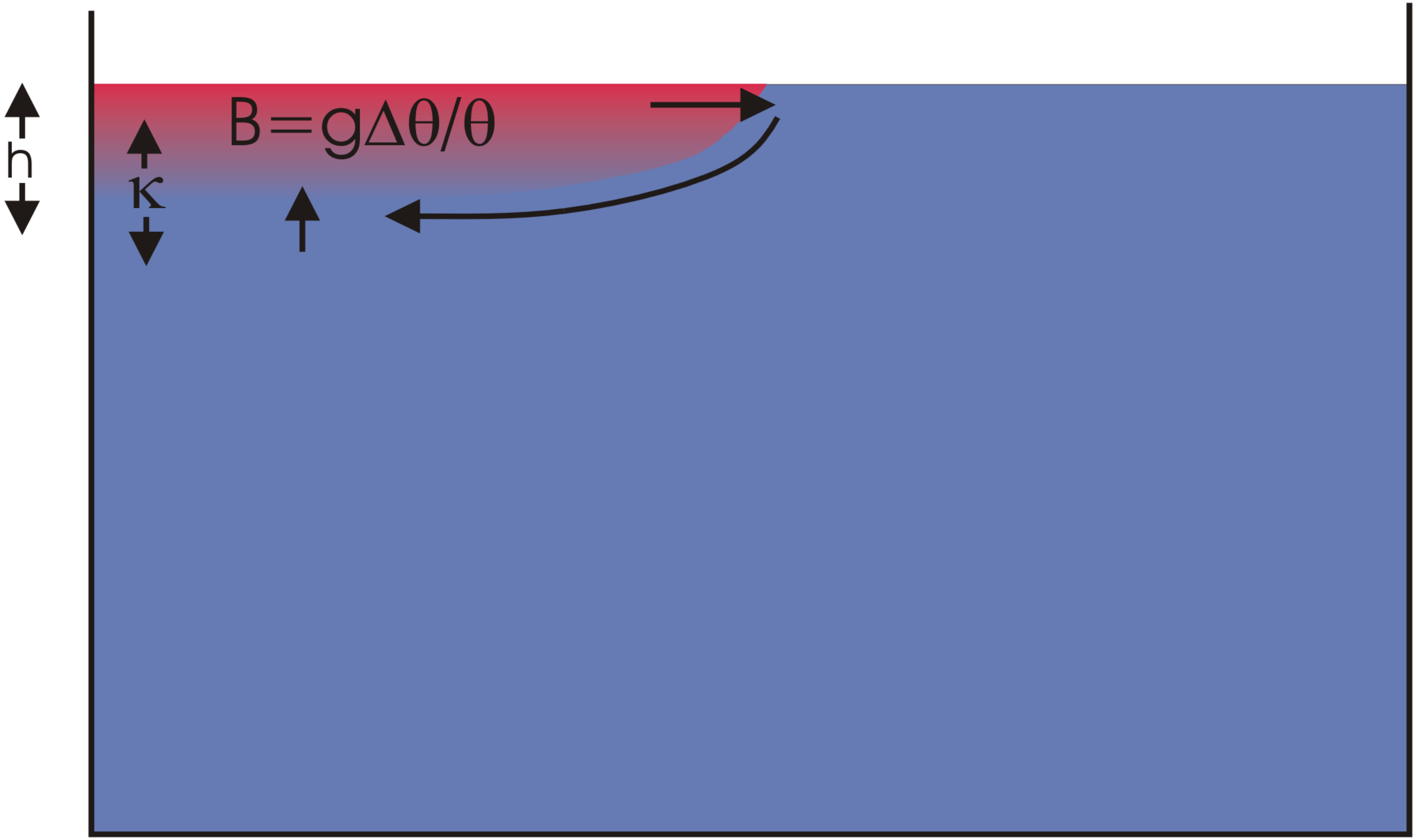
Ocean Thermohaline Circulation



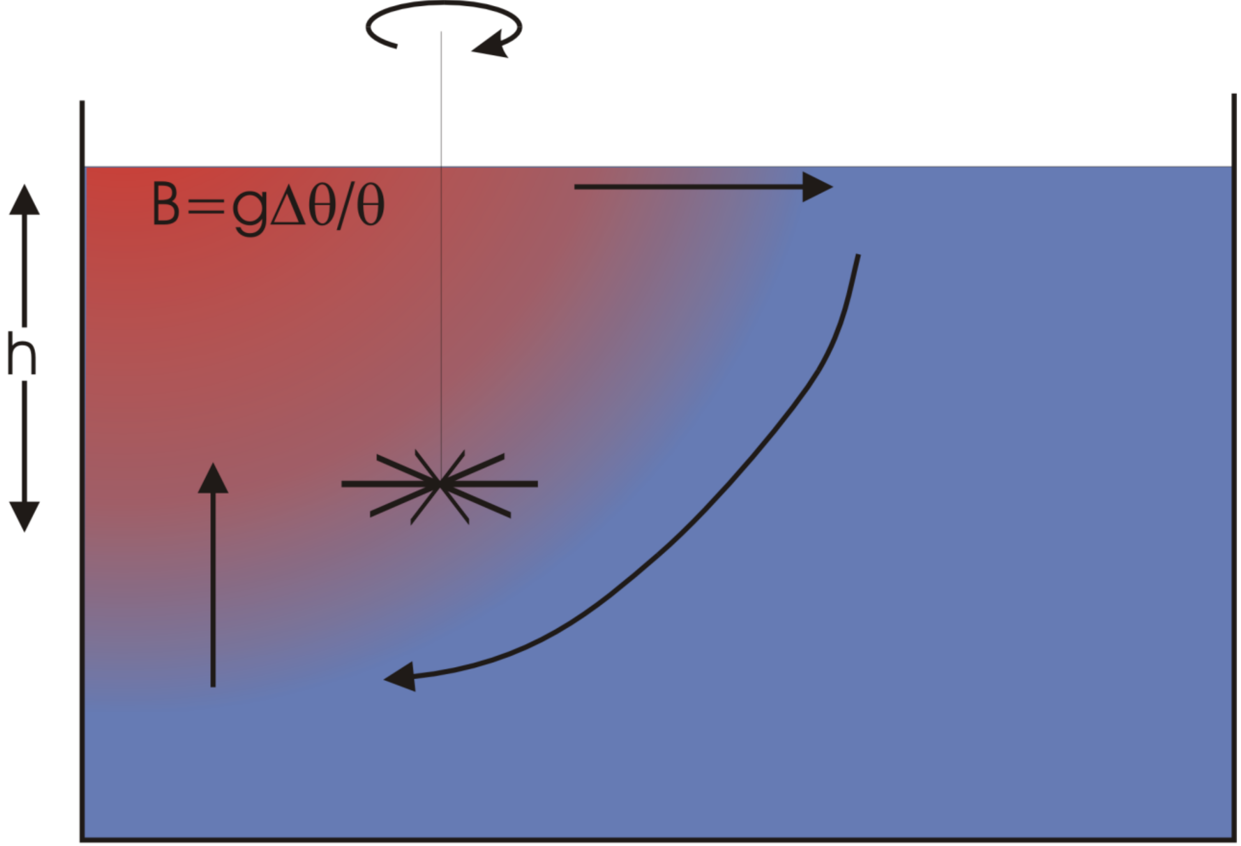
Source: Broecker, 1991, in Climate change 1995, Impacts, adaptations and mitigation of climate change: scientific-technical analyses, contribution of working group 2 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge press university, 1996.



Heat Transport by Oceans and Atmosphere



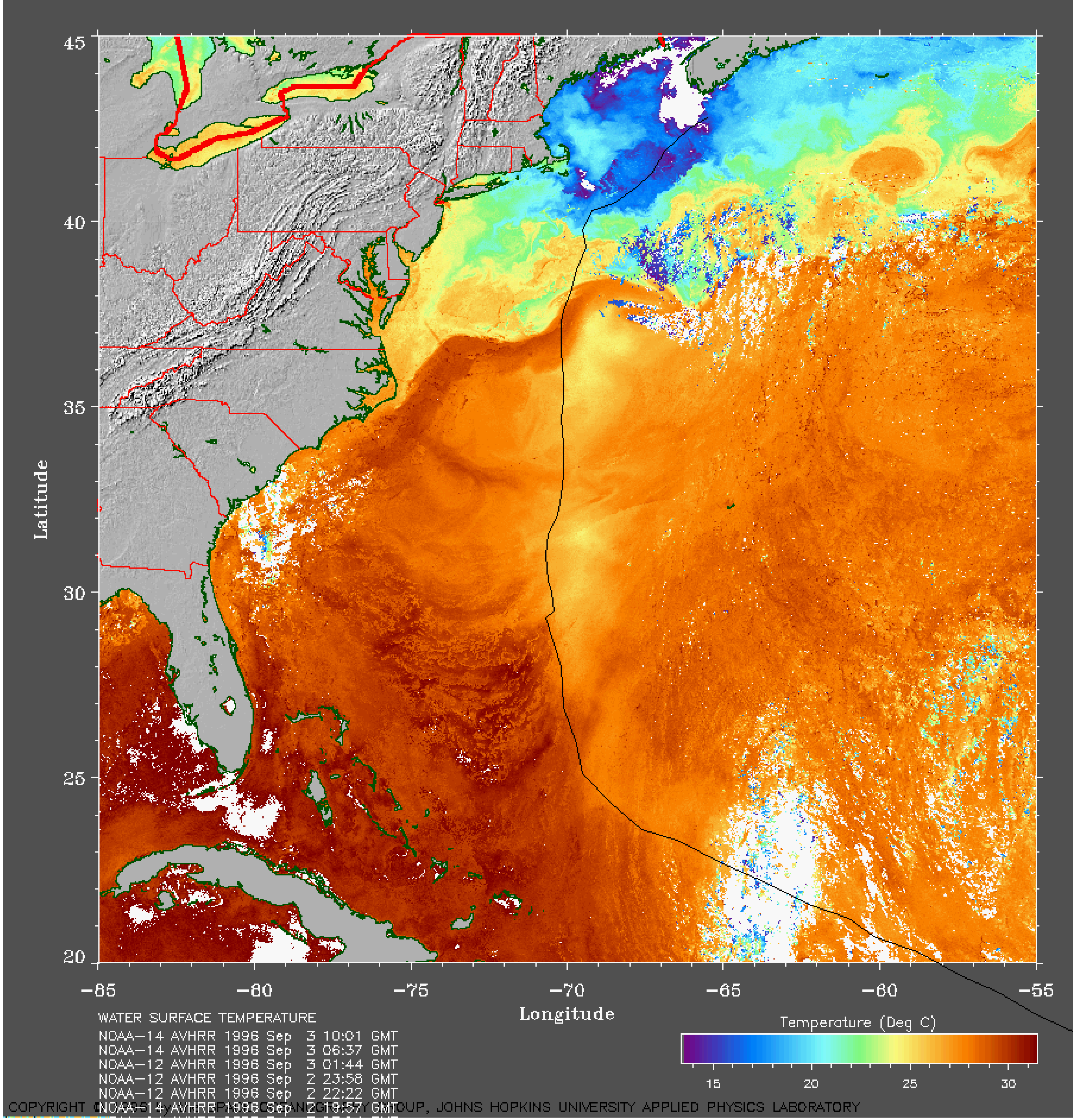
A hot plate is brought in contact with the left half of the surface of a swimming pool of cold water. Heat diffuses downward and the warm water begins to rise. The strength of the circulation is controlled in part by the rate of heat diffusion. In the real world, this rate is very, very small.



$$\text{Heat Flux} \sim P^{2/3} B^{2/3}$$

$$h \sim P^{1/3} B^{-2/3}$$

Adding a stirring rod to this picture greatly enhances the circulation by mixing the warm water to greater depth and bringing more cold water in contact with the plate. The strength of the lateral heat flux is proportional to the 2/3 power of the power put into the stirring, and the 2/3 power of the temperature of the plate.



WATER SURFACE TEMPERATURE
NOAA−14 AVHRR 1996 Sep 3 10:01 GMT
NOAA−14 AVHRR 1996 Sep 3 06:37 GMT
NOAA−12 AVHRR 1996 Sep 3 01:44 GMT
NOAA−12 AVHRR 1996 Sep 2 23:58 GMT
NOAA−12 AVHRR 1996 Sep 2 22:22 GMT
NOAA−14 AVHRR 1996 Sep 2 19:57 GMT

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Coupled Ocean-Atmosphere model run for 67 of the 83 tropical cyclones that occurred in calendar year 1996

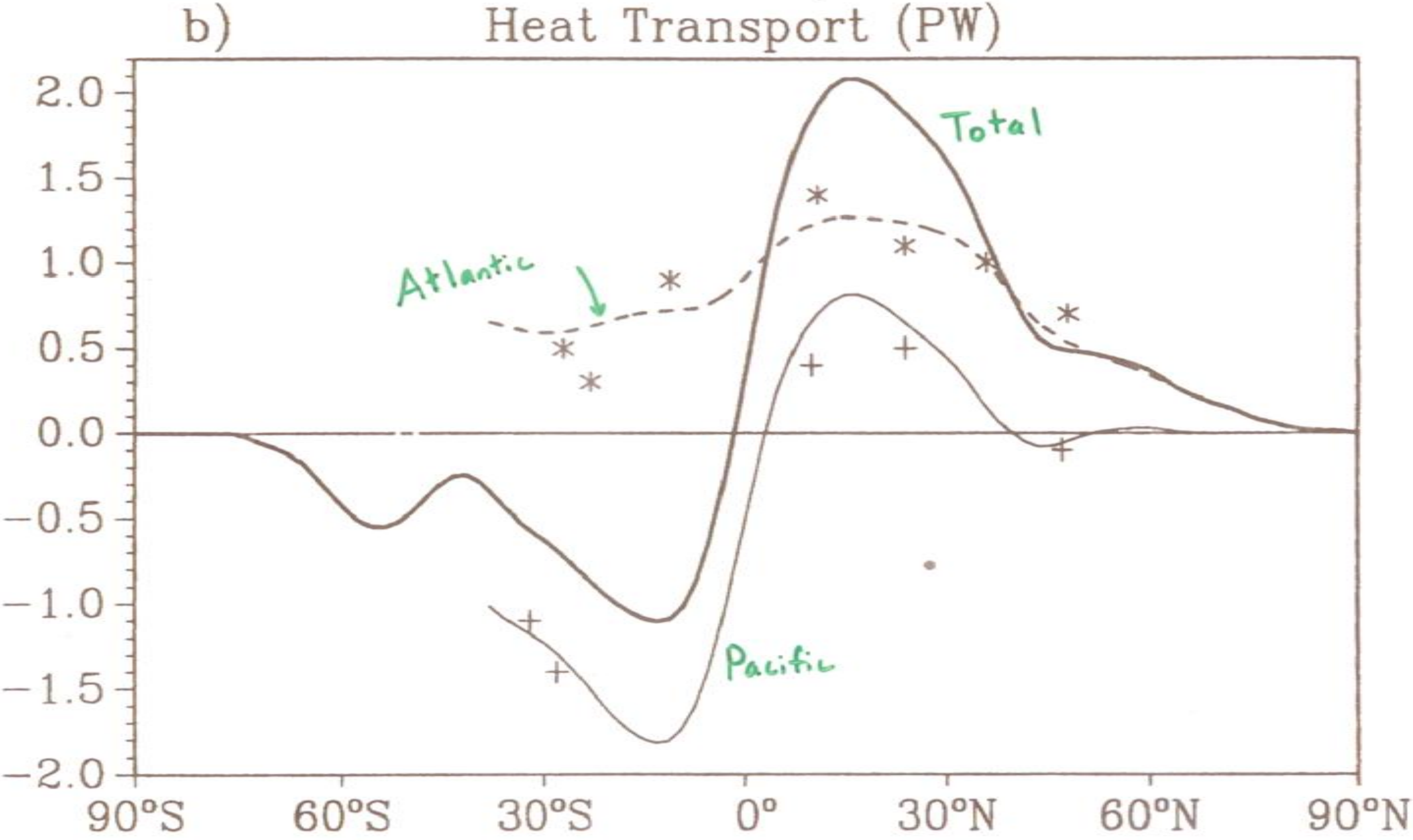
Accumulated TC-induced ocean heating divided by 366 days

Result:

Net column-integrated heating of ocean induced by global tropical cyclone activity:

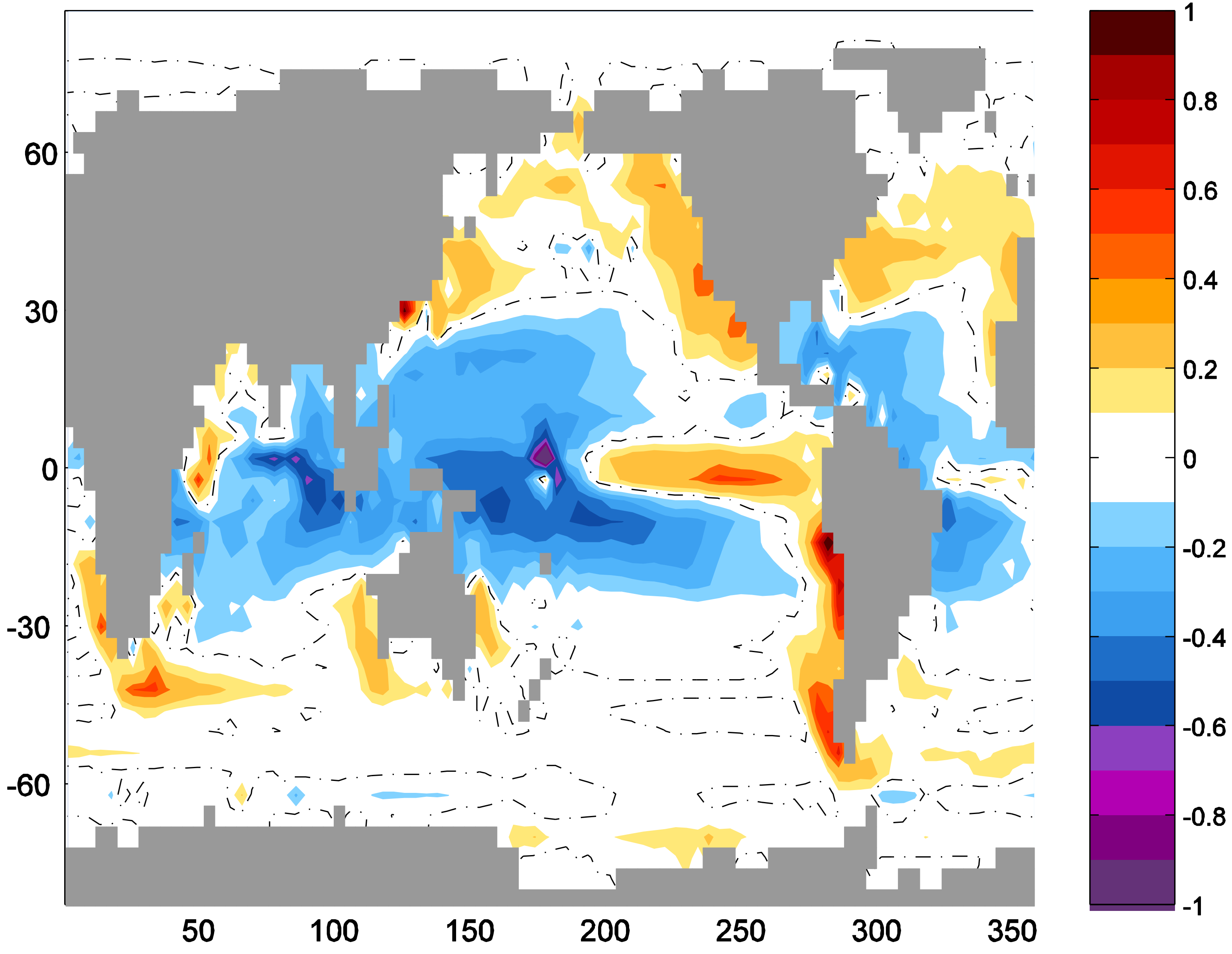
$$\left(1.4 \pm 0.7\right) \times 10^{15}\, W$$

Trenberth et al., 2001



Transient experiment by Rob Korty

$\Delta SST = SST_{hurricanes} - SST_{uniform\ mixing}$



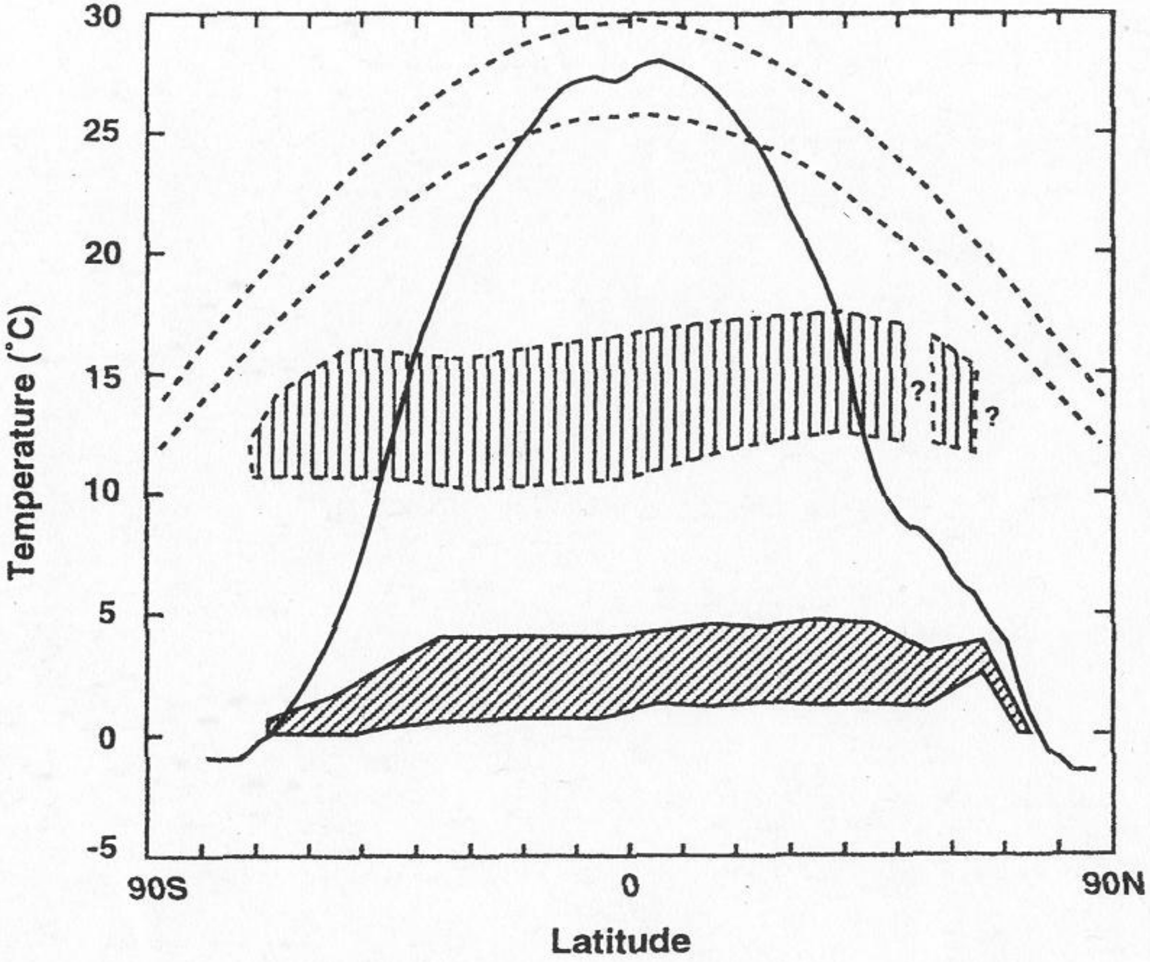


Figure 4.1. Modern (solid line) and estimated early Eocene (dashed lines) zonal sea surface temperatures. Modern (diagonal hatch) and estimated early Eocene (vertical hatch) water temperatures at bottom depths between 1000 m and 5000 m. Modern data are from the *World Ocean Atlas data set* (Levitus and Boyer, 1994). The cooler Eocene SST profile is based on Zachos *et al.* (1994); the warmer SST profile is based on Crowley and Zachos (Chapter 3, this volume).

Summary

- Hurricanes are almost perfect Carnot heat engines, operating off the thermodynamic disequilibrium between the tropical ocean and atmosphere, made possible by the greenhouse effect
- Most hurricanes are prevented from reaching their potential intensity by storm-induced ocean cooling and environmental wind shear

- Hurricanes result from a finite-amplitude instability of the tropical ocean-atmosphere system
- Hurricane-induced mixing of the upper ocean may be the main driver of the ocean’s deep overturning circulation, an important component of the climate system